

CR 172098

NASA Contractor Report AS-EVALS-FR-8701

Extravehicular Activities Limitations Study

Volume 1 - Physiological Limitations to Extravehicular Activity in Space

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Prepared for
Lyndon B. Johnson Space Center
under Contract NAS-9-17702



National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1988

N89-17392

Unclas
0185224

(NASA-CR-172098) EXTRAVEHICULAR ACTIVITIES
LIMITATIONS STUDY. VOLUME 1: PHYSIOLOGICAL
LIMITATIONS TO EXTRAVEHICULAR ACTIVITY IN
SPACE Final Report (Grumman Aerospace
Corp.) 269 p CSCL 06S 63/52



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FOREWORD

This report (No. AS-EVALS-FR-8701) is submitted by the Grumman Corporation, Space Systems Division (GSSD) to the Lyndon B. Johnson Space Center, NASA as part of the work performed under Contract NAS 9-17702: Extravehicular Activities Limitations (EVA) Study. The report represents the Final Report as per DRL No. T-2064, Line Item No. 1, DRD No. MA-183TF.

The report is submitted in two volumes. Volume I presents the results of Phase I: "Physiological Limitations to Extravehicular Activity in Space" with the exception of SOW Task 2.8: "Hand mobility, dexterity, and fatigue." Volume II presents the results of Phase II: "Establishment of Physiological and Performance Criteria for EVA Gloves" and Phase I SOW Task 2.8.

The work was performed for NASA under the technical direction of David J. Horrigan, Jr. (SD5), Head, Environmental Physiology, NASA JSC.

The conclusions and opinions presented in the report are those of the authors alone and are not necessarily consistent with those of NASA or GSSD.

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CONTENTS

<u>Section</u>		<u>Page</u>
1	DESCRIPTION OF STUDY	1-1
1.1	Contributors	1-1
1.2	Introduction	1-1
1.2.1	Objective	1-2
1.3	Procedure for Literature Search & Evaluation	1-2
1.3.1	Selection of Informational Databases	1-2
1.3.2	Selection of References Within a Database	1-3
1.3.3	Evaluation of References	1-3
1.3.4	Criteria for Selection into Database	1-3
1.4	Review of Advanced EVA Systems Design Requirements Studies	1-4
1.4.1	McDonnell Douglas Astronautics Corporation	1-4
1.4.2	Boeing Aircraft Company	1-7
1.4.3	Grumman Corporation	1-10
1.5	The Human Role in Space - MDAC	1-11
1.6	Analysis of EVA Manhours/Year from AEVAS Studies	1-16
1.6.1	Estimates of EVA Manhours per 90 Day Mission per EVA Astronaut	1-16
1.7	References	1-16
2	OPTIMUM WORK DURING EVA	2-1
2.1	Introduction	2-1
2.2	Salient Work Capacity Research	2-2
2.3	EVA Work Influence Factors	2-29
2.3.1	Physiological Adaptation	2-29
2.3.2	Astronaut Population Considerations	2-32
2.3.3	Space Environmental Factors	2-34
2.3.4	EVA Task Structure	2-38
2.4	EVA Work Optimization	2-51
2.4.1	Sortie Duration & Frequency	2-51
2.4.2	EVA Life Support System Requirements	2-55

CONTENTS (contd)

<u>Section</u>	<u>Page</u>
2.4.3 Physical Features of the Suit & Gloves	2-60
2.4.4 Ancillary Work Aids	2-63
2.4.5 Task Structuring	2-65
2.5 Final Remarks	2-68
2.6 References	2-68
 3 FOOD & WATER	 3-1
3.1 Summary of EVA Metabolic Energy Expenditure	3-1
3.2 Nutrient Requirements	3-3
3.2.1 Food	3-6
3.2.2 Water	3-7
3.2.3 Combined Effects on Food & Water	3-8
3.2.4 Nutrient Requirements & Energy Expenditure	3-10
3.3 Effect of Hydration on the Incidence of Decompression Sickness	 3-11
3.4 Electrolytes	3-14
3.4.1 Bone & Calcium	3-14
3.5 Loss of Circulating Red Blood Cell Mass	3-16
3.6 Vitamin & Mineral Supplementation	3-17
3.7 In-Suit Feeding vs Lunch Break	3-20
3.7.1 Advantages to In-Suit Feeding	3-22
3.7.2 Disadvantages of In-Suit Feeding	3-22
3.7.3 Advantages to Taking a Lunch Break	3-23
3.7.4 Disadvantages of a Lunch Break	3-24
3.8 Conclusions & Recommendations	3-26
3.9 References	3-27
 4 OXYGEN LEVELS	 4-1
4.1 Introduction	4-1
4.1.1 Hypoxia	4-1
4.1.2 Hyperoxia	4-1
4.2 Mild Hypoxia	4-2
4.2.1 Acclimatization to Hypoxia	4-5

CONTENTS (contd)

<u>Section</u>	<u>Page</u>
4.2.2 Pharmacological Intervention in Hypoxia.	4-7
4.3 Hyperoxia	4-10
4.3.1 Pulmonary Function.	4-10
4.3.2 Circulating Red Blood Cell Mass	4-16
4.4 Exposure to 8 Plus PSIA PO ₂ during EVA	4-19
4.5 Summary	4-22
4.6 Recommendations for Further Studies	4-23
4.7 References	4-23
 5 CARBON DIOXIDE LEVELS	 5-1
5.1 Introduction.	5-1
5.2 Carbon Dioxide Production during EVA	5-1
5.2.1 Diet	5-2
5.2.2 Physical Activity	5-2
5.3 Present EMU Primary Life Support System (PLSS)	5-4
5.4 Acute Effect of Breathing a Gas Enriched with Carbon Dioxide	 5-4
5.5 Chronic Effects of Breathing Elevated Levels of Carbon Dioxide	 5-5
5.6 Effects of Breathing Carbon Dioxide during Exercise.	5-9
5.7 Basis for Establishing Carbon Dioxide Limits during EVA.	 5-13
5.8 Current Standards	5-16
5.9 Conclusions & Recommendations	5-17
5.10 References	5-18
 6 PHYSIOLOGICAL EFFECTS OF REPETITIVE DECOMPRESSIONS & RECENT ADVANCES IN COMPRESSION SICKNESS RESEARCH . . .	 6-1
6.1 Introduction.	6-1
6.2 Overview of the Space Atmospheric Selection Problem	6-2
6.3 Review of the Etiology of Decompression Sickness	6-2
6.4 Review of Preventive Measures to Reduce DCS Problems . . .	6-3
6.4.1 Preoxygenation . . . :	6-3

CONTENTS (contd)

<u>Section</u>	<u>Page</u>
6.4.2 Nitrogen Equilibration	6-3
6.5 Anticipated Crewmember Tasking for Space Station.	6-4
6.6 Review of Repetitive Decompression Sickness Research.	6-5
6.6.1 Effects of Repeated Exposure to Subatmospheric Pressure on DCS Symptomatology	6-6
6.6.2 Studies Indicating Increased Susceptibility to DCS.	6-6
6.6.3 Studies Indicating No Change or Decreased Susceptibility to DCS.	6-9
6.6.4 Conclusions	6-12
6.7 Metabolic & Other Factors Complicating the Effects of Repetitive Decompressions during Prolonged Space Flight	6-13
6.7.1 General	6-13
6.7.2 Literature Review	6-13
6.8 Optimal Countermeasures Against the Potential Effects of Decompression Sickness.	6-16
6.9 Recommendations for Further Studies	6-20
6.10 References	6-22
7 THERMAL BALANCE	7-1
7.1 Introduction.	7-1
7.2 Thermal Regulation in General & Under EVA Conditions.	7-1
7.3 Scope of Study & Study Limitations	7-2
7.4 Effect of Changes in Ambient Temperature on EVA Work Performance	7-3
7.4.1 Effect of Increased Core Temperature.	7-4
7.4.2 Effect of Lowered Core Temperature	7-5
7.4.3 Effect of Skin Temperature.	7-6
7.5 Effect of Multiple Environmental Stressors on EVA Work Performance	7-6
7.6 Other Factors Affecting Work Performance	7-7

CONTENTS (contd)

<u>Section</u>	<u>Page</u>
7.7 Effect of Thermal Heating & Cooling Devices on EVA Work Performance	7-7
7.8 Limits	7-10
7.9 Research Recommendations	7-11
7.10 References	7-12
8 URINE COLLECTION	8-1
8.1 Introduction	8-1
8.2 Methodology	8-1
8.3 Results	8-2
8.3.1 Familiarization During Training	8-2
8.3.2 UCD Experience During Actual EVA	8-2
8.4 Discussion	8-3
8.5 Conclusions & Recommendations	8-4
 <u>APPENDIX</u>	
A	A-1
B	B-1
C	C-1

ILLUSTRATIONS

<u>Fig.</u>		<u>Page</u>
1-1	Total EVA Mission Manhour Requirements for the Space Station Program	1-5
1-2	Estimated EVA Manhour Requirements Considering Firmness Ratings	1-6
1-3	Estimated EVA Mission Manhour Requirements for Space Station Core	1-7
1-4	Total EVA Missions Plus ORU Manhours (MDAC)	1-8
1-5	Total EVA Missions Plus ORU Manhours (FRE)	1-9
1-6	EVA Manhours Per Year (Max)*	1-12
1-7	EVA Manhours Per Year (Firm)*	1-12
1-8	EVA Manhour Requirements (Space Station Task Force - MRWG Mission Model)	1-15
2-1	Static Load Capacity as a Function of Holding Time	2-3
2-2	Maximum Sustainable Metabolic Rate as a Function of Total Work Interval	2-6
2-3	Metabolic Rates for Selected Physical Activities Superimposed on the Lehmann Work-Capacity Curve to Illustrate the Magnitude of Possible Excursions	2-10
2-4	Comparison of Work Capacity Limits of Lehmann & Bink et al for Intervals from 5 min to 30 hr (1800 min)	2-15
2-5	Comparison of Work Capacity Limits of Lehmann & Bink et al for Intervals from 5 min to 8 hr	2-16
2-6	Rest Allowance Required as a Function of the Number of Task Repetitions for Various Fractions of Maximum Holding Time. Applied Force (k) Equal Half Maximum Strength (K) for All Three Curves.	2-21
2-7	Variations in Running Performance for Various Work/Rest Intervals; with the Same Burst Work Intensity (27 kcal/min) & Total Work Period (30 min) during All Test Runs	2-24

ILLUSTRATIONS (contd)

<u>Fig.</u>		<u>Page</u>
2-8	Blood Lactate Concentration During 30 min Total Work Intervals for Various Burst/Pause Intervals. Total Work (15,120 Kpm) & Burst to Pause Ratio (1:4) the Same During All Sessions	2-26
2-9	EVA Work Influence Factors	2-28
2-10	Comparison of Actual EVA Average Metabolic Rate Data with Lehmann Sustained Maximum Work Capacity Limit Curve	2-39
2-11	EVA Metabolic Support Requirements for Planned Workloads Without Excursion Allowances	2-57
2-12	EVA Life Support System Specifications	2-58
2-13	EVA Contingency Life Support System Requirements	2-59
3-1	Quantitative Parameters of Physical Work Capacity of Test Subjects	3-19
3-2	Heart Rate of the Test Subjects Before (a) & After (b) Exercise	3-20
3-3	Suit Pressure vs Airlock/Crewlock Pressure for EVA Cycle	3-25
4-1	The Alveolar Oxygen & Carbon Dioxide Tensions During Acute Exposure to Simulated Altitudes Whilst Breathing Air. Mean Values for a Series of Subjects (With the Standard Deviation of the Mean) are Given at Each Altitude. The Broken Lines Depict the Alveolar Gas Tensions Which Would Result if No Ventilatory Response Occurred to Anoxia. (Boothby, 1944.)	4-6
4-2	The Relationship Between Alveolar Oxygen Tension & Pulmonary Ventilation in the Steady Physiological State at Alveolar Carbon Dioxide Tensions of 39•6 mm Hg (•), 45•6 mm Hg (o), and 49•3 mm Hg (x). (Cormack et al, 1957.)	4-7
4-3	Physiological Responses to Hypoxia	4-8
4-4	Sequence of Acute Physiologic Effects of Oxygen in Normal Men	4-12
4-5	Pulmonary Oxygen Tolerance Curves in Normal Men (Based on Vital Capacity Changes in 50% of the Subjects)	4-13

ILLUSTRATIONS (contd)

<u>Fig.</u>		<u>Page</u>
4-6	Pulmonary Oxygen Poisoning Susceptibility for Normal Men (Based on a 4% Decrease in Vital Capacity)	4-14
4-7	Prediction of Oxygen Tolerance Extension by Periodic Interruption of Oxygen Exposure	4-15
4-8	EVA Schedules, Case I & II	4-20
4-9	EVA Schedules, Case III	4-21
4-10	Increase in Suite PO_2 as 100% O_2 Replaces Suit Leakage	4-22
5-1	The Response of Awake, Healthy Men to Inhalation of Increasing Concentrations of CO_2 in Air	5-5
5-2	U.S. Navy's Official Judgement on the Hazards of Short-Term Exposures to CO_2	5-8

TABLES

<u>Table</u>		<u>Page</u>
1-1	Total EVA Mission Timeline Summary	1-10
1-2	Prioritized List of EVA Missions	1-11
1-3	IVA & EVA Task Time Comparisons, Fine Motor Movements	1-14
1-4	IVA & EVA Task Time Comparisons, Coarse Motor Movements	1-15
2-1	Cumulative Metabolic Output Following Lehmann Work Protocol.	2-8
2-2	Productive Work Output Following Lehmann Protocol.	2-9
3-1	Metabolic Expenditures During Extravehicular Activities.	3-5
3-2	Proportions of Protein, Fat & Carbohydrates in U.S. Adults, Athletes, Astronauts & USSR Cosmonauts	3-5
3-3	Bone & Calcium Changes Associated with Short-Term & Long-Term Space Flight	3-15
3-4	Average Time Spent by the Test Subjects in Solving Arithmetic Logic Problems	3-19
4-1	Drugs Affecting Physiological & Metabolic Responses to Acute Hypoxia	4-9
5-1	Energy Expenditure for Various Activities	5-3
6-1	Recurrence of Bends on Reascent (Rodbard, 1944)	6-7

ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
AEVAS	Advanced EVA System Design Requirements Study
BCD	Baseline Configuration Document
CNS	Central Nervous System
CO ₂	Carbon Dioxide
DACT	Disposable Absorption Collection Truck
DCS	Decompression Sickness
DOD	Department of Defense
ECLSS	Environmental Control & Life Support System
EMU	Extravehicular Maneuvering Unit
EVA	Extravehicular Activity
EVAS	Extravehicular Activity System
FAR	Federal Aviation Regulations
FEV ₁	Forced Expiratory Volume - first
FICO ₂	Inspired Fraction of Carbon Dioxide
FRE	Functional Requirements Envelope

ACRONYMS (Contd)

GEO	Geosynchronous Orbit
HBO	Hyperbaric Oxygen
IMP	Impervious Protective Garment
IOC	Initial Operating Capability
IVA	Intravehicular Activity
LCG	Liquid-Cooled Garment
LED	Light Emitting Diode
LEO	Low Earth Orbit
MDAC	McDonnell Douglas Astronautics Corp
MMF	Maximum Mid-expiratory Flow
MEF	Maximum Expiratory Flow
NBC	Nuclear, Biological & Chemical
NIOSH	National Institute of Occupational Safety & Health
N ₂	Nitrogen
NSMRL	Naval Submarine Medical Research Laboratory
NTIS	National Technical Information Service
O ₂	Oxygen

ACRONYMS (Contd)

PAO ₂	Alveolar Partial Pressure of Oxygen
PaO ₂	Arterial Partial Pressure of Oxygen
PACO ₂	Alveolar Partial Pressure of Carbon Dioxide
PaCO ₂	Arterial Partial Pressure of Carbon Dioxide
PCO ₂	Partial Pressure of Carbon Dioxide
PF	Peak Flow
PICO ₂	Inspired Partial Pressure of Carbon Dioxide
PLSS	Primary Life Support system
PO ₂	Partial Pressure of Oxygen
R	Respiratory Exchange Ratio
RAF	Royal Air Force
RBC	Red Blood Cell
RCM	Red Blood Cell Mass
RDA	Recommended Daily Allowance
RFP	Request for Proposal
RQ	Respiratory Quotient
SCRT	Serial Choice Response Time

ACRONYMS (Contd)

SOW	Statement of Work
THURIS	The Human Role in Space
TWA	Time Weighted Average
UCD	Urine Collection Device
UPDT	Unit Pulmonary Toxicity Dose
VC	Vital Capacity
WBC	White Cell Count
WETF	Water Emersion Test Facility

1 - DESCRIPTION OF STUDY

Volume I of the Final Report presents the result of the Phase I effort: "Physiological Limitations to Extravehicular Activity (EVA) in Space."

The work presented in Volume I represents the collaboration of the following individuals and institutions:

1.1 CONTRIBUTORS

The following personnel/institutions collaborated in collecting, analyzing and conducting tests in pursuit of this study:

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1.2 INTRODUCTION

The American physiologist, Walter P. Cannon, in his book "Wisdom of the Body" emphasized that the human body possessed a remarkable ability to adapt to changes in its internal and external environment. It should be emphasized, as Leach and Rambaut pointed out in 1977, that many of the physiological changes

associated with space flight are physiologic; that is, they represent normal adaptations in order to establish a homeostasis appropriate to the new environment. Homeostasis in the weightless environment is achieved after a period of cardiovascular deconditioning, muscle atrophy, bone demineralization, etc. In studying the physiology of weightlessness, the physiologist must: (1) determine the impact of homeostatic change in terms of acceptable work performance, and (2) determine how much change is acceptable without jeopardizing the astronauts' eventual safe return to Earth. To determine the effect of weightlessness on work capacity, research on work capacity in the one-g environment has been the baseline for EVA work performance predictions, modified by Water Emersion Test Facility (WETF) and actual EVA data.

1.2.1 Objective

The objective of this effort was to establish an informational database to predict the limits of human work performance during (EVA), and to provide design requirements for space suit designers. From a physiological point of view, the ideal space suit should provide man with his accustomed Earth environment. However, the zero gravity and zero pressure of the EVA environment, as well as cost and engineering constraints, limit the extent to which space suits and associated life support system can be designed to provide an Earth-like environment. The problem facing the physiologist and the design engineer is to design a suit that maximizes EVA work capacity while providing an acceptable, healthy environment that minimizes physiological stress on the EVA astronaut. Maximizing EVA work while minimizing physiological stress requires a thorough knowledge and understanding of the EVA environment, and man's limitations to it.

1.3 PROCEDURE FOR LITERATURE SEARCH & EVALUATION

The development of the Physiological Limitations to EVA in Space Study database was accomplished in three phases:

- Selection of informational databases to be searched
- Selection of references within the informational databases
- Evaluation of selected references.

1.3.1 Selection of Informational Databases

The databases to be searched were determined after consultation with Mr. Tom Rees, Grumman librarian with many years experience searching aerospace medicine

databases, and after consultation with Mr. Robert Jack, NASA JSC librarian who developed the NASA informational database. The databases searched were:

- NASA RECON - Past 25 years
- MEDLINE - Past 20 years
- EXCERPRA MEDICA - Past 13 years
- NTIS - Past 15 years
- DTIC - Past 20 years.

1.3.2 Selection of References Within a Database

In selecting references within a database, a list of search terms was developed for each Statement of Work (SOW) topic. References selected included those of general, as well as specific relevance, to the search topic. In other words, this first set of references selected by the computer included not just references on physiological factors limiting EVA and other space-related work, but also references on physiological factors affecting work performance in Earth-normal and adverse conditions. From this initial set of general and specific references (typically numbered in the thousands), the computer selected those related to the subject of interest (SOW topics). The selection was made by combining search terms and using the combined search terms to select references for evaluation. The citations for the selected references were stored on floppy diskettes. The specific search terms and numbers of references identified for each are listed by subject in Appendix A. (Search combinations which did not give references are not listed.)

1.3.3 Evaluation of References

The evaluation of selected references involved several steps. First, a criteria was developed to determine whether or not a particular reference would be evaluated further and if it should be included in a database. This criteria was based on an examination of the title, abstract (if available), and key words for each reference. Articles were then obtained and reviewed for inclusion into a database.

1.3.4 Criteria for Selection into Database

The following criteria were used in selecting references from the various databases for inclusion into this report:

- Physiological changes, particularly in relation to work/performance
- General/generic interest relative to space operations
- Applicability to other SOW topics.

The effort began with a review of three 1985 studies; one each by the Grumman Corporation, McDonnell Douglas Astronautics Corporation (MDAC), and the Boeing Aircraft Company entitled "Advanced Extravehicular Activity Systems Design Requirements Study," and a 1984 MDAC study entitled "The Human Role in Space."

1.4 REVIEW OF ADVANCED EVA SYSTEMS DESIGN REQUIREMENTS STUDIES

During the period December 1985 to March 1986, McDonnell Douglas Astronautics Corporation, Boeing Aircraft Company and the Grumman Corporation each submitted reports entitled "Advanced EVA System Design Requirements Study (AEVAS)" [1,2,3]. In these reports estimates of EVA time by year were made based on information gathered primarily from the Langley Mission Database. These estimates are summarized here along with caveats stipulated by each organization.

1.4.1 McDonnell Douglas Astronautics Corporation

MDAC [1] estimates that of 324 total missions referenced in the Langley Mission Database, 141 would require some sort of EVA support. They identified 15 generic missions for Space Station EVA:

- Alignment of transmitter/receiver elements
- Deploy/retract solar array
- Truss structure construction
- Satellite service technology
- Large modules manipulation
- Small module manipulation
- Large mirror construction
- Consumables recharge via module manipulation
- Orbit launch operations
- Satellite operations
- Space Station radiator construction (from orbiter)
- Orbiter supported large module manipulation
- Orbiter supported truss construction/deployment
- Radiator construction - full up Space Station
- EVA rescue.

From these, they arrived at a minimum estimate of slightly more than 1000 manhours of EVA time per year would be required at Space Station Initial Operating Capability (IOC), and that within two years approximately 4300 manhours would be

required per year for all the missions noted in the Langley Mission Database, Fig. 1-1. MDAC notes two caveats, or problems with these estimates. First, it includes polar missions which probably will not be supported with EVA from the Space Station; and second, it includes many missions which have only a very low probability of flying. The missions were therefore ordered on a scale from 1 to 5; with 1 indicating a mission that was certain to fly, and a 5 indicating a mission which would almost certainly not fly. A new sum of EVA manhours required per year was generated, this time including only those missions with a firmness rating of 1, 2, or 3, plus 20% of the time required for those missions with a firmness of 4, Fig. 1-2. When all polar missions are removed from MDAC's estimates, the times noted in Fig. 1-3 is the result. As a result, 346 manhours of EVA time was estimated to be required in the first year of Space Station operations, increasing to a maximum of 1512 manhours per year in the seventh year. MDAC cautions that two caveats go

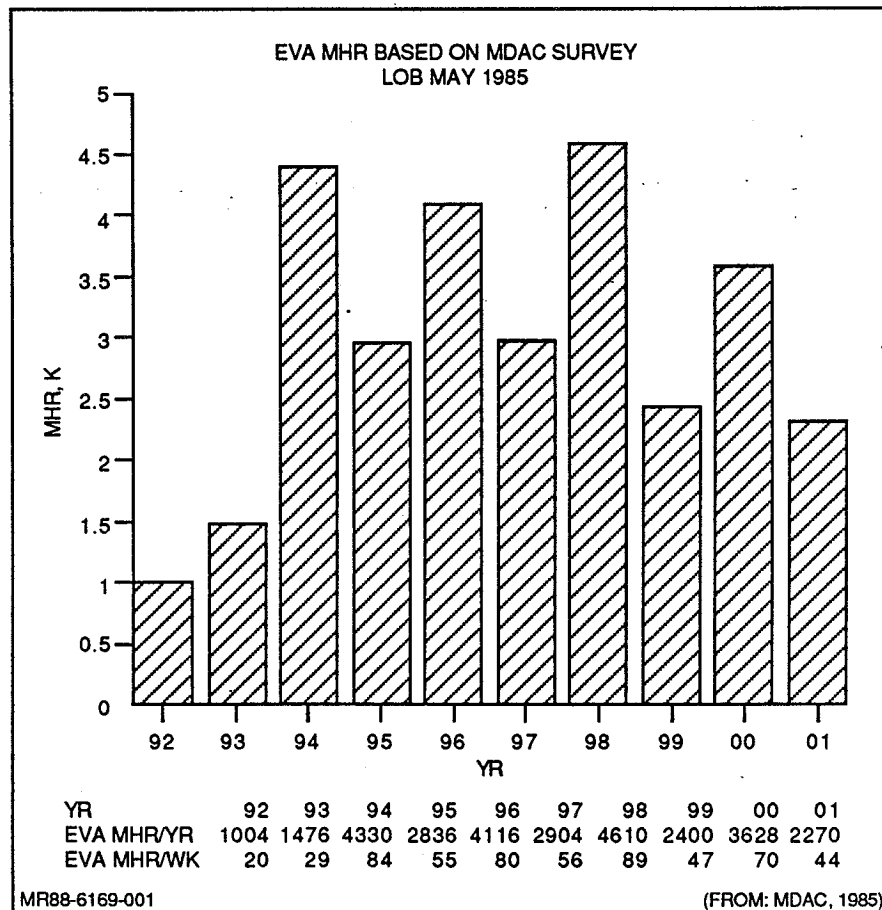


Fig. 1-1 Total EVA Mission Manhour Requirements for the Space Station Program

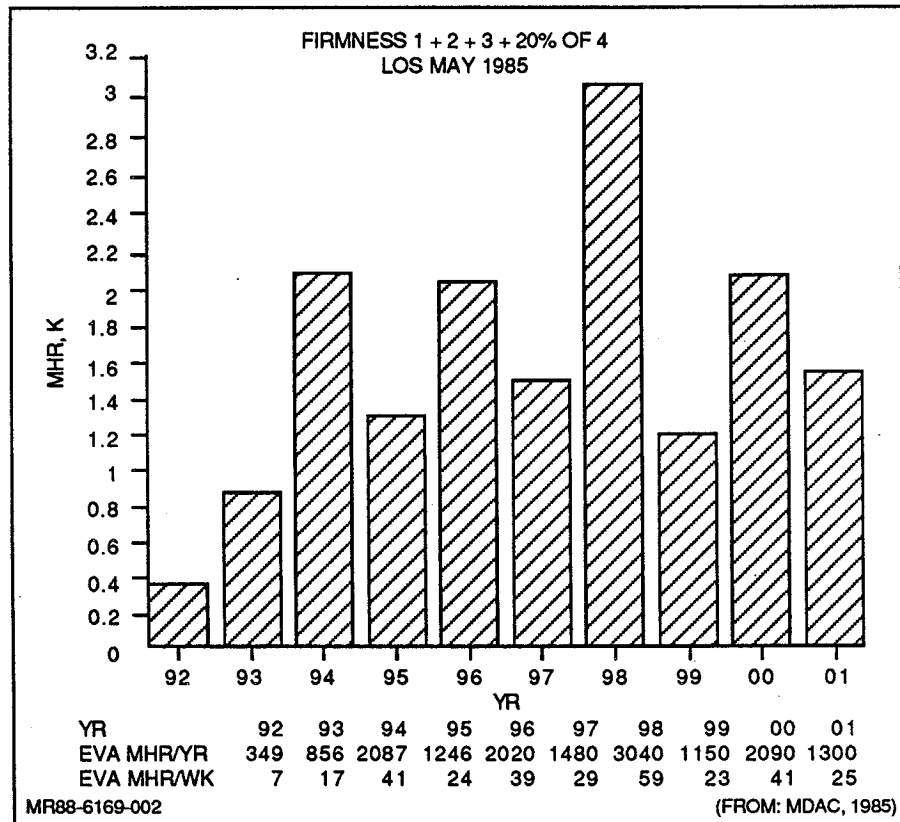


Fig. 1-2 Estimated EVA Manhour Requirements Considering Firmness Ratings

with these estimates. First, the estimates are heavily dependent on guesswork about mission operations 15 years in the future; and second, a "tail-off" phenomenon exists after the third year of Space Station operation, indicating that few experimenters and payload sponsors wish to guess about events so far in the future. They further caution that; "This yields what is probably a false tail-off in required EVA hours in the latter years covered by the estimates and causes such estimates as exist to consist heavily of firmness 4 missions, yielding a further reduction due to our weighting procedure."

MDAC further cautions that these are rough estimates containing numerous caveats; and furthermore, they are "extremely conservative," citing that Skylab and Shuttle experience indicate that "unplanned EVA mission requirements tend to exceed planned requirements by approximately 2 to 1." In addition to the above analysis, an allocation of 1192 EVA manhours per year was made for Space Station maintenance. By combining Space Station maintenance hours with the estimates for EVA shown in Fig. 1-3, MDAC presents figures showing a minimum requirement of

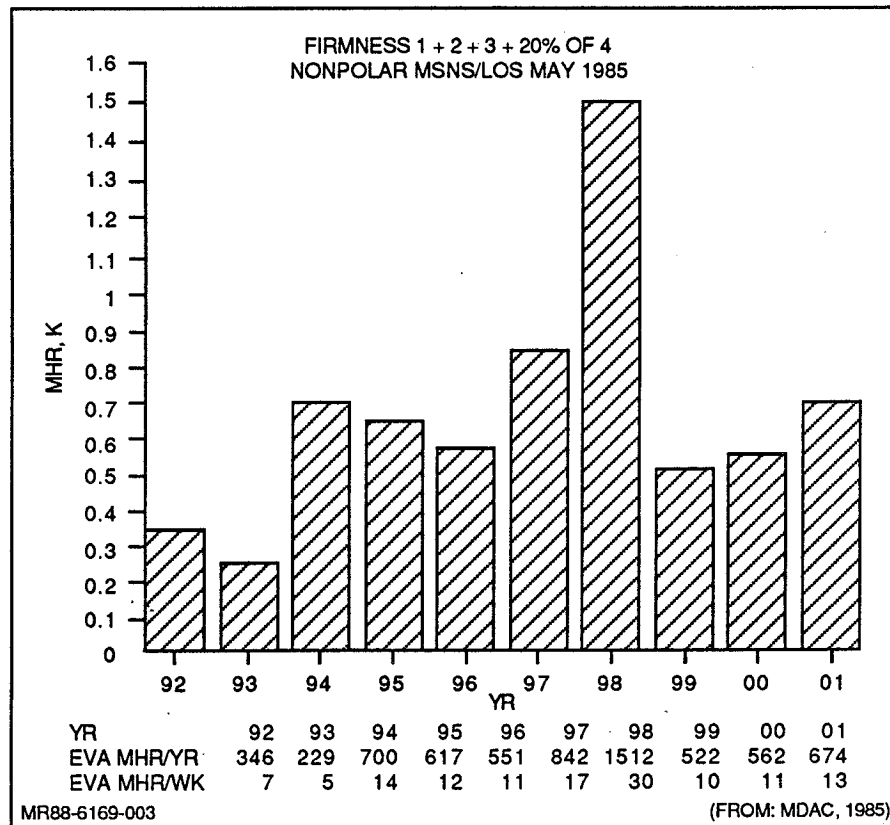


Fig. 1-3 Estimated EVA Mission Manhour Requirements for Space Station Core

just over 1500 EVA manhours per year at IOC, growing to 2700 manhours per year within six years, (for Space Station maintenance - MSN and orbital replaceable units ORU), Fig. 1-4. MDAC points out that these figures compare to those defined by the Functional Requirements Envelope (FRE) forwarded by NASA in May 1985, Fig. 1-5. MDAC concludes by stating that; "The most significant preliminary conclusion to be drawn from our EVA manhours requirements data (or the FRE) is that, even with the stated caveats, the required amount of EVA will far exceed that which could be provided by the current Shuttle Extravehicular Activity System (EVAS). In fact, it quickly approaches EVA crew physiological limits as defined both by the Baseline Configuration Document (BCD) and by past (Shuttle) EVA experience."

1.4.2 Boeing Aircraft Company

In their study, Boeing [2] conducted a mission requirements survey utilizing the Langley Mission Database as well as other sources. From this analysis they identified and prioritized 199 EVA missions which they grouped into 11 categories:

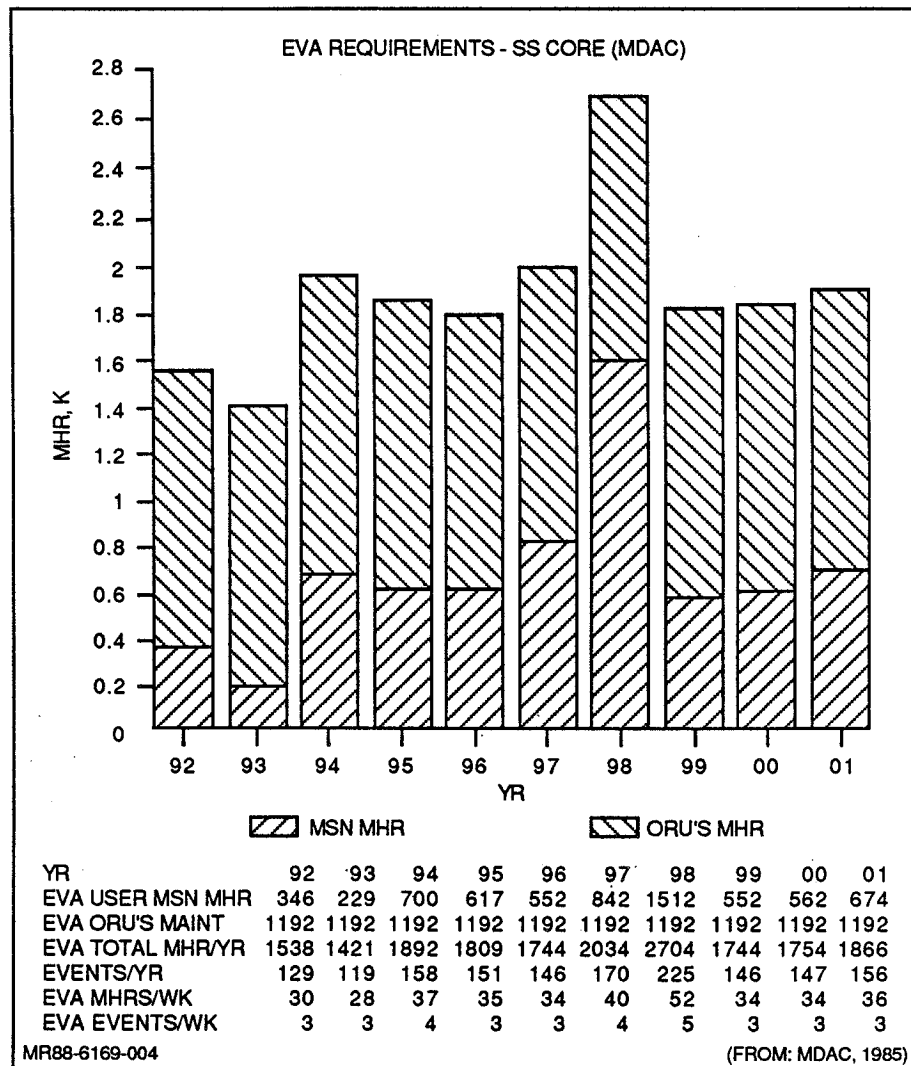


Fig. 1-4 Total EVA Missions Plus ORU Manhours (MDAC)

- Large satellite servicing
- Small and medium satellite servicing
- Large satellite launch (solids)
- Large satellite launch (liquids)
- Small and medium satellite launch
- Platform servicing at Low Earth Orbit (LEO)
- Platform servicing at Geosynchronous Earth Orbit (GEO)
- Platform servicing at Polar
- Large space structure assembly
- On station installation and servicing
- Test and evaluation.

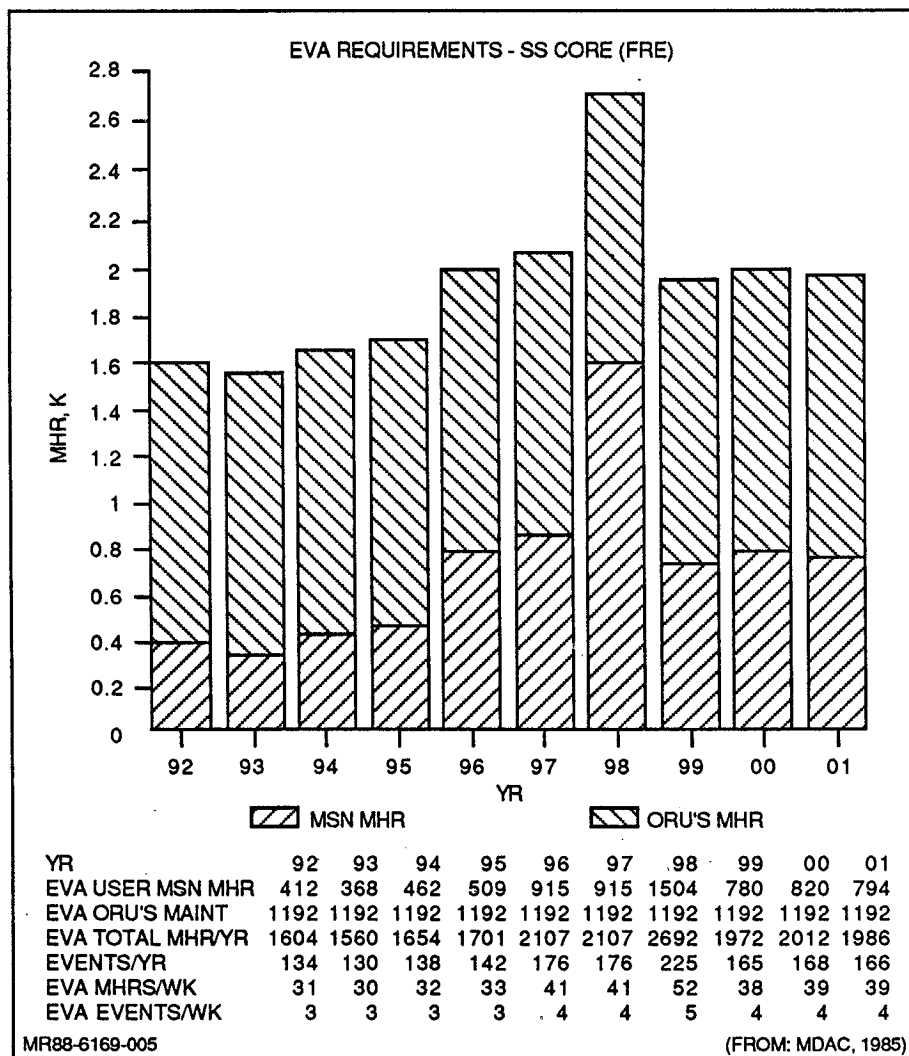


Fig. 1-5 Total EVA Missions Plus ORU Manhours (FRE)

Utilizing the MDAC "The Human Role in Space" (THURIS) study and other technical studies, existing EVA task data was converted to generic EVA tasks. These were then analyzed relative to an analysis of EVA missions with the result that a final EVA generic task list containing 74 tasks (excluding DOD tasks) was generated. In addition, a mission unique list of generic EVA tasks was identified which was then used to generate functional flow diagrams for each mission. This allowed for the identification of time phasing and sequencing of tasks and activities. An EVA generic task versus EVA mission matrix was then constructed as well as matrices showing EVA generic tasks versus other EVA systems and parameters (EVAS equipment, tools, restraints, etc).

From a generic task versus mission matrix, frequency and total times for each task and mission was computed allowing Boeing to estimate timelines for each EVA mission. Based on their evaluation of the Phase B Request for Proposal (RFP) EVA allocations, a six man crew (all engaging in EVA), and 18 hours per week EVA per person, a maximum of 1872 hours per year would be available for EVA. Whereas in their Total EVA Mission Timeline Summary, Table 1-1, they show a requirement for 2712 EVA manhours per year at Space Station IOC. In their estimation this will not be enough EVA time two years post-IOC (up to 5224 manhours per year at IOC plus 8 years). These times take into consideration "two crewmen effectiveness of working together and improving with experience."

1.4.3 Grumman Corporation

Also utilizing the Langley Mission Database, Grumman [3] prioritized a list of EVA missions in order of firmness, Table 1-2. This data was compared to the projected Space Station EVA capability. An estimate of this capability was computed

Table 1-1 Total EVA Mission Timeline Summary

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Space Station less Polar COML, TDMX, SAAX	2274	3806	4512	4209	3938	4260	4444	4271	4080	3891
Space Station maintenance & repair hr	1200	1200	1200	1200	1800	2400	2400	3000	3600	3600
Total EVA serial mission hr	3474	5006	5712	5409	5738	6660	6844	7271	7680	7491
Overhead	200 + 225	200 + 741	200 + 727	200 + 628	300 + 445	400 + 487	400 + 572	500 + 435	600 + 476	600 + 495
Productive mission* hr required	3049	4065	4785	4581	4993	5773	5872	6336	6604	6396
Number of crews	2	2	2	2	4	4	4	6	6	6
Crew effectiveness index	1.333	1.471	1.563	1.613	1.486	1.568	1.615	1.538	1.592	1.627
EVA manhr**	2712	3704	3988	3668	4105	4568	4608	5055	5224	5026
Available hr Surplus/Def.	3744 + 1032	3744 + 40	3744 -244	3744 + 76	7488 + 3383	7488 + Large	7488 + Large	11232 + Large	11232 + Large	11232 + Large
(From: Boeing, 1985)										

* NOTE 1: IOC crew of two; first growth crew of four; second growth crew of six

** NOTE 2: EVA manhr = (Productive mission hr required + crew effectiveness) x number of crews + overhead 100% crew effectiveness = 2 for a crew of two; 0% effective = 1 for a crew of two

Scheduling efficiency = 100%. No contingencies. No EVA equipment downtime. No sickness. No mistakes.

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Table 1-2 Prioritized List of EVA Missions*

Order of firmness	Number of missions	Number of EVA hours
Operational	= 2	28 + (1 mission n/a)
Approved (funded)	= 3	312 + (1 mission n/a)
Planned	= 39 (+ 6 S/S)	3,069 + (25 missions n/a)
Candidate	= 56	12,086 + (18 missions n/a)
Opportunity	= 24	424 + (11 missions n/a)
TOTALS	= 124 (+ 6)	TOTAL HOURS = 15,917
(Total of 56 missions EVA time not available)		
*Source: NASA Langley mission database updated February 1985		
R88-6169-006		(From: Grumman 1985)

by employing the EVA ground rules and guidelines contained in the Phase B Space Station RFP and the AEVAS RFP:

- No solo EVA allowed
- Maximum of 4 persons engaged in EVA at one time
- 80 hours of EVA per week (flexible)
- Maximum of 8 hours of EVA per person per day
- 18 hours of EVA per person per week (flexible).

Computing the Space Station's maximum annual EVA requirements was achieved by combining the Langley Mission Database EVA requirements with an estimate of EVA hours required for maintaining the Space Station plus a contingency allowance of 10%. The results are shown in Fig. 1-6. Figure 1-7 shows EVA manhours per year if only the "firm" missions are considered - operational, funded and planned. Grumman did not categorize the Langley Mission Database into generic EVA missions as was done by MDAC and Boeing.

1.5 THE HUMAN ROLE IN SPACE - MDAC

In September of 1984 McDonnell Douglas Astronautics Corporation released a report entitled; "The Human Role in Space" (THURIS) [4]. This study; (1) investigated the role and the required degree of direct involvement of humans in future space missions, (2) established criteria for the allocation of functional

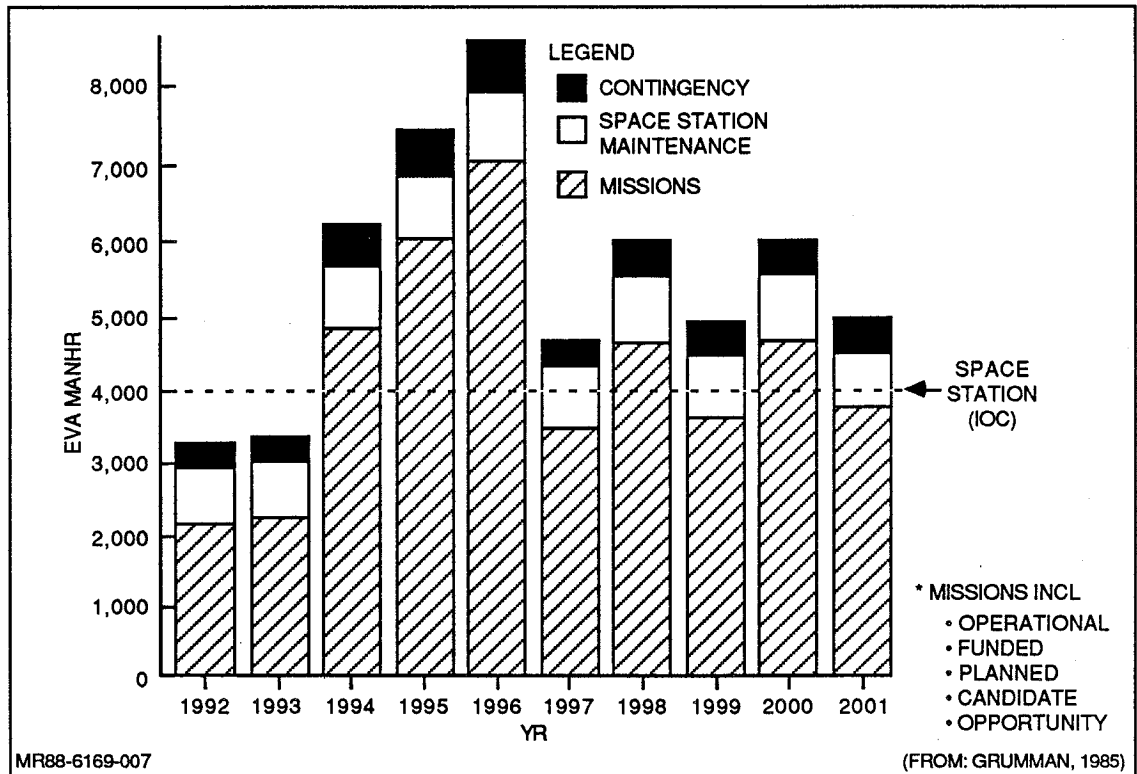


Fig. 1-6 EVA Manhours Per Year (Max)*

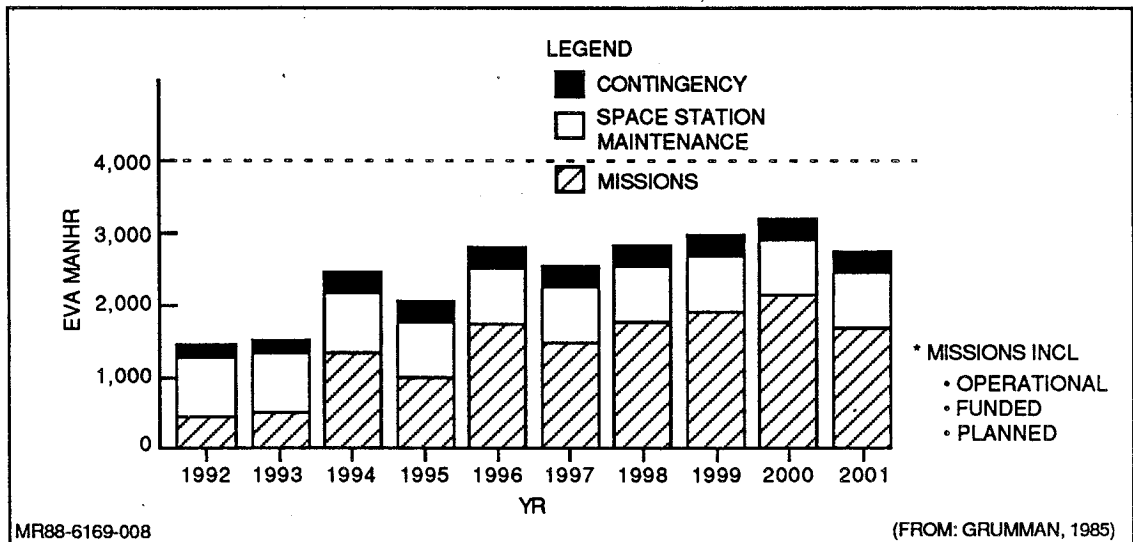


Fig. 1-7 EVA Manhours Per Year (Firm)*

activities between humans and machines, and (3) investigated the technology requirements, economics, and benefits of the human presence in space. The result was a methodology for space activity allocation based on criteria of performance, cost, and technological readiness for 37 unique generic space activities:

- Activate/initiate system operation
- Adjust/align elements
- Allocate/assign/distribute
- Apply/remove biomedical sensors
- Communicate information
- Compensatory tracking
- Compute data
- Confirm/verify procedures/schedules/operations
- Connect/disconnect electrical interfaces
- Connect/disconnect fluid interfaces
- Correlate data
- Deactivate/terminate system operation
- Decode/encode data
- Define procedures/schedules/operations
- Deploy/retract appendages
- Detect change in state or condition
- Display data
- Gather/replace tools/equipment
- Handle/inspect/examine living organisms
- Implement procedures/schedules
- Information processing
- Inspect/observe
- Measure (scale) physical dimensions
- Plot data
- Position module
- Precision manipulation of objects
- Problem solving/decision making/data analysis
- Pursuit tracking
- Release/secure mechanical interfaces
- Remove module
- Remove/replace coverings
- Replace/clean surface coatings

- Replenish materials
- Store/record elements
- Surgical manipulations
- Transport loaded
- Transport unloaded.

These activities involve both man and robotic intravehicular activity (IVA) and EVA tasks. One part of the THURIS study involved IVA and EVA task time comparisons for fine and coarse motor movements. MDAC found that it took 50% longer to do fine motor movement tasks with the pressurized gloved hand (EVA/IVA ratio of 1.53), Table 1-3. For coarse motor movement tasks the time required with the gloved hand was about the same as for the bare hand (EVA/IVA ratio of 1.09), Table 1-4. The foregoing times/ratios represent activities by fully suited astronauts versus SCUBA divers participating in neutral buoyancy tests.

One of MDAC's objectives in the THURIS study was to identify the requirements for technological developments needed to enable and enhance the human role in future space activities, both IVA and EVA. In their review of NASA planning documents, and particularly the then current Mission Model developed by the Mission Requirements Working Group of the Space Station Task Force, MDAC projected the yearly EVA manhours beginning in 1992 (the IOC date for Space Station as projected at the time of the THURIS report). They estimated a requirement for 2026 manhours with lesser demands during the subsequent 4 years, Fig. 1-8. This estimate was based upon a six man crew.

Table 1-3 IVA & EVA Task Time Comparisons, Fine Motor Movements

Task	Average times (sec)		Ratio EVA/IVA
	IVA	EVA	
Electrical connectors			
Coax - 6 turns, threaded	19	31	1.63
Bayonet - 120 deg lock/unlock	8	14	1.75
Fluid interface			
Remove	10	13	1.30
Install	14	20	1.44
Average			1.53

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Table 1-4 IVA & EVA Task Time Comparisons, Coarse Motor Movements

Task	Average times (sec)		Ratio EVA/IVA
	IVA	EVA	
Manual hand crank			
3-in. radius	20	21	1.05
6-in. radius	22	24	1.09
9-in. radius	23	26	1.13
Average			1.09

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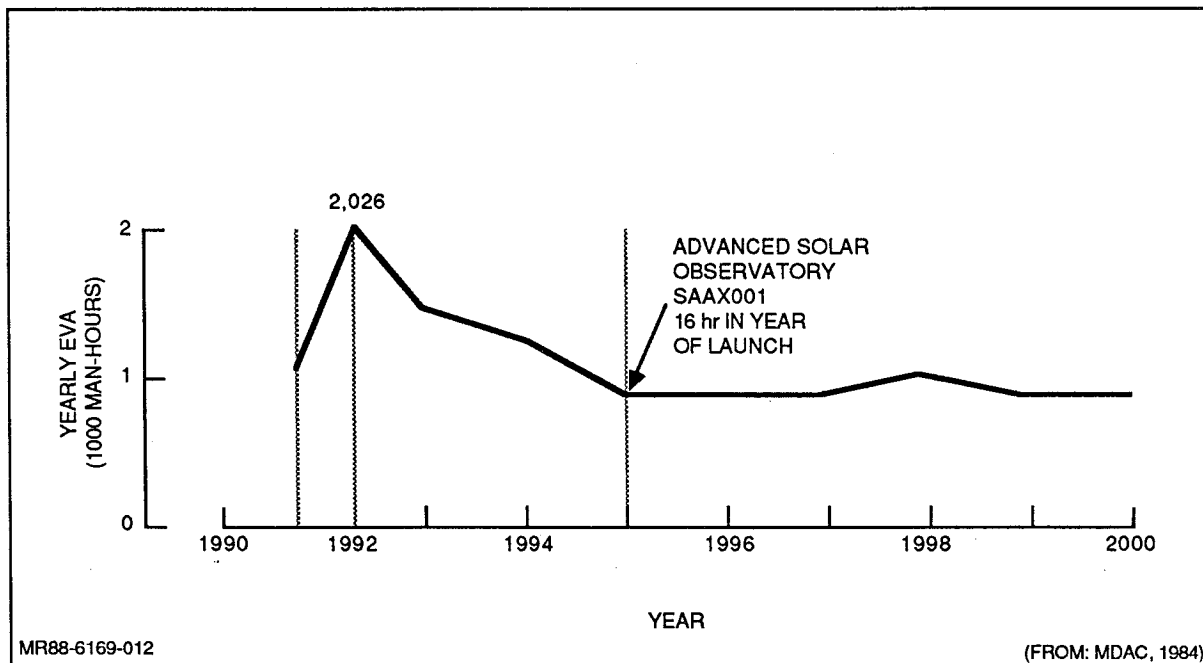


Fig. 1-8 EVA Manhour Requirements (Space Station Task Force - MRWG Mission Model)

1.6 ANALYSIS OF EVA MANHOURS/YEAR FROM AEVAS STUDIES

The estimates by Boeing, Grumman, and MDAC, of required EVA manhours per year, vary greatly due to a variety of reasons: (1) different interpretations of the EVA requirements to support the various missions as defined by such documents/studies as the Langley Mission Database, (2) varying definitions of categories of missions as to operational, approved, funded, planned, candidate, and EVA missions of opportunity, (3) varying estimates of the probability of a mission flying, or firmness of the mission, (4) crew size, (5) whether or not EVA missions will be flown on certain orbits (e.g., polar orbits), (6) varying estimates of future participation in space by commercial firms, and (7) human factor considerations such as EVA astronaut productivity. The estimates of EVA manhours per year contained in the THURIS study vary even more from those given in the three AEVAS studies. This study was done at an earlier time and in response to a different requirement.

1.6.1 Estimates of EVA Manhours per 90 day Mission per EVA Astronaut

If the highest estimate of EVA manhours taken from the three AEVAS studies for any year (e.g., 5224 - Boeing) is broken down to the number of hours per man per 90 day Space Station mission, two astronauts will be required to engage in EVA 50 hours per week. If EVA tasks are divided between four astronauts, the number falls to 25 hours per week. This is 7 hours per week more than called out in the AEVAS RFP (18 hr/wk/EVA astronaut). Of course, if six astronauts handle the EVA chores, each would spend 17 hours per week EVA.

Finally, if as stated in the SOW Paragraph 1.0, there were a cadre of astronauts specifically selected to engage in EVA as their primary function on Space Station, they could be required to engage in EVA up to 8 hours per day for up to 40 hours per week if it can be shown to be feasible physiologically. This equates to 4160 manhours per year for two astronauts, which would allow for pursuing EVA missions categorized as "soft" (e.g., missions of opportunity).

1.7 REFERENCES

1. Advanced EVA System Design Requirements Study. McDonnell Douglas Astronautics Corporation. Report No. MDC W0072, January 1986.

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2. Advanced EVA System Design Requirements Study. Grumman Corporation. Document No. SE-1094T, December 1985.
3. Advanced EVA System Design Requirements Study. Boeing Corporation. Report D180-28806-1, March 1986.
4. The Human Role in Space. McDonnell Douglas Astronautics Corporation. Report No. MDC H1997, December 1985, Huntington Beach, CA.

2 - OPTIMUM EVA WORK

The Optimum Work section is in response to Sections 2.0 and 2.4 of the SOW of the RFP; it was researched by Robert L. Santoro and Donald H. Peterson and was prepared by Mr. Peterson.

2.1 INTRODUCTION

The term "optimum work" for the purposes of this study has been defined by NASA to mean that EVA tasks should be structured, scheduled, and executed in ways that will utilize astronaut physiological work capacity as effectively and efficiently as possible. Accordingly, Grumman defined two objectives for this study. First, to the extent possible with existing data, we derived guidelines and criteria for the design of equipment, the development of procedures and techniques, and the implementation of scheduling protocols that would enhance the attainment of EVA objectives for a given investment of physiological effort. Second, we identified study areas in which further research offers potential benefits.

To accomplish these objectives, we reviewed and assessed the relatively large body of existing literature on physiological work capacity. Then we scrutinized EVA training and mission data to identify and understand the effects of the environmental, operational, and engineering factors that influence physiological performance during EVA. Finally, we analyzed the combined information from these two efforts to derive EVA physiological work optimization guidelines and criteria and to identify research areas that appear to have the greatest potential for producing further improvements in EVA work performance.

The remainder of this section is divided into three subsections. The first presents the salient information extracted from the literature on work physiology research. The second consists of a brief description of the dominant EVA work influence factors. The final subsection presents specific EVA work optimization findings. Recommendations for further research are interspersed throughout the text wherever they are believed to be appropriate.

2.2 SALIENT WORK CAPACITY RESEARCH

A relatively large body of information on physiological work capacity exists. Much of it, especially early research, focuses on the clinical aspects of human strength, work output, and endurance (and its counterpart, fatigue). In most of this research effort, pseudo-tasks were carefully structured to elicit specific physiological responses and hence they are not particularly representative of real world work. Some researchers, however, have generalized and extended these results to include typical real-world tasks and working conditions. Of particular interest to our study are those results that define general limits of human work capacity and the use of so-called "work/pause cycles" to enhance cumulative performance. These results are discussed below. The primary sources of information for this subsection are reference works by Ernst Simonson, Physiology of Work Capacity and Fatigue; E. Asmussen, A Companion to Medical Studies; and McArdle et al, Exercise Physiology. The reader who wishes more detail is referred to these references.

Physiological "work," as presented in the literature, consists of two fundamentally different kinds of effort: static and dynamic. Static effort consists of the exertion of force (or torque) against an unmoving resistance (e.g., holding a weight at a fixed height above the floor, or holding a spring extended or compressed at a fixed position). Static effort does not truly constitute work by the rigorous physics definition. However, it does require physical exertion that leads to fatigue, and in common parlance a fatiguing effort is usually referred to as "work." Consequently, static effort is usually called static work (or workload). The unit of measurement of static work is the mathematical product of force (or torque) times the duration of effort (i.e., force x duration).

Several characteristics of static work are especially important to this study. First, Simonson emphasizes that all work includes a static component, because maintenance of posture and stabilization of body parts is essential whether the primary workload is static or dynamic. Furthermore, many of the muscle groups involved in posture and stability are not those that are directly involved in the primary work activity [1, p. 241]. Consequently, measurements of fatigue or metabolic energy expenditure as a function of a typical primary workload (e.g., holding a weight against gravity or pedaling an exercycle) will inevitably include some component induced by the indirect static effort. In cases where the magnitudes of the primary workload and the indirect load are comparable, the measured correlations among

metabolic rate, induced fatigue, and output workload (i.e., the external, mechanical workload) may be substantially altered.

Surprisingly, the functional relationship between "pure" static loads and endurance (fatigue) does not change appreciably from subject to subject, or from one muscle group to another, if the metric applied to each subject/muscle group is normalized as a percentage of the maximum strength of that individual/muscle group. For example, Subject A can exert 50% of his maximum arm strength for the same length of time that Subject B can exert 50% of his maximum leg strength. Research results from W. Rohmert that define this relation are shown in Fig. 2-1 [1, p. 246]. Clearly, endurance (called "holding time" in Fig. 2-1) is very short for loads that exceed 30% of the maximum load. Endurance increases rapidly for loads below 30% of maximum load, however, and there is a threshold value at about 15% of maximum strength below which fatigue does not occur and for all practical purposes endurance becomes essentially unbounded (i.e., holding times exceed 8 hours of continuous application) [1, p. 248].

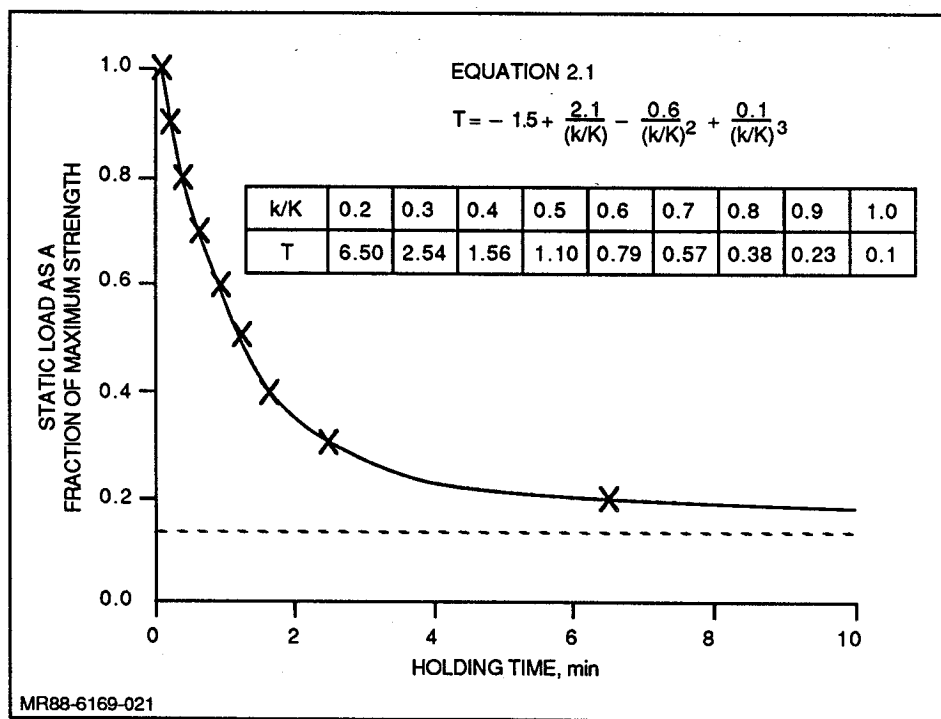


Fig. 2-1 Static Load Capacity as a Function of Holding Time

The metabolic energy expenditure associated with a given degree of fatigue induced by static work is disproportionately small by comparison with the metabolic energy expenditure associated with that same degree of fatigue induced by dynamic work [1, p.242]. Stated another way, for a given level of excess metabolic energy (i.e., metabolic energy above the normal resting level) the onset of fatigue is much more rapid in static work than in dynamic work. Asmussen [2, p. 42.1] states: "The energy cost of static effort is astonishingly low. One subject maintained a tension of about 100 Kp (220 lbf) for 20 minutes with a metabolism of only about twice the resting level." If we assume a 95th-percentile male test subject (210 lb) [3], the metabolic rate while sitting quietly is about 2.0 kcal/min [4]. Thus, using Asmussen's estimate that the task required twice that amount of energy, we would surmise that a metabolic rate of about 4.0 kcal/min existed while holding 220 lbf with the legs. This metabolic rate is equivalent to the rate that would be generated by a man this size playing a woodwind musical instrument or painting an interior wall [4] - a level that is indeed astonishingly low. (Note: This example is astonishing for another reason as well. The holding time of 20 minutes implies, from the data in Fig. 2-1, that this load is less than 15% of the subject's maximum leg strength. If true, then this subject is able to lift about 1467 lb with his legs, which is also somewhat astonishing.)

An example, presented by Simonson [1, pp. 257-8] indicates that oxygen uptake increased from a resting value of about 350 ml/min to a maximum of about 930 ml/min during a sustained leg lift of 70 lb for an interval of 7 minutes. Simonson also states that lifts of 100, 130 and 160 lb in this same series showed that oxygen uptake "...during work increased in linear proportion of the load..." Based upon the accepted average conversion factor, one liter of oxygen is consumed for each 4.825 kcal of metabolic energy produced, and thus the energy level associated with a 70-lb static leg lift in this experiment was about 4.5 kcal/min.

We must point out that these two examples are not consistent. Simonson states that metabolic rate is proportional to load, but his example indicates a higher metabolic energy level for a 70-lb leg lift (4.5 kcal/min) than does Asmussen's example of a 220-lb leg lift (4.0 kcal/min). We cannot resolve this contradiction; in fact, there is not a large database in this area, and what does exist is often not consistent. In

part, these inconsistencies probably result from the difficulty inherent in trying to precisely measure relatively small metabolic loads under less than ideal measurement conditions, such as those that are normally encountered when a subject is performing strenuous effort. This is an area where further basic research is needed to provide a more precise, consistent database.

Regardless of their differences, the authors of our selected references did agree on two aspects of metabolic energy levels during static work. First, the increase in metabolic energy is very small for relatively heavy (greater than 40% of maximum) loads that induce fatigue quite rapidly (less than 10 minutes). Second, unlike the universal relationship between normalized load and endurance (illustrated in Fig. 2-1), the relationship between fatigue and energy level varies from subject to subject and from muscle group to muscle group. The general trend seems to support Simonson's statement that heavier loads require higher metabolic rates, but the relationship apparently cannot be reduced to a single curve (as was done for the load/fatigue relationship in Fig. 2-1.)

By comparison with static work research, the database that relates energy costs, fatigue and dynamic work (which, incidentally, conforms to the physics definition of work) is more comprehensive and consistent. The most general relationship between endurance and workload appears to be a set of tabular data produced by G. Lehmann (*Praktische Arbeits Physiologic*, Stuttgart, Thieme, 1962) which is discussed by Simonson [1, p. 449]. Lehmann's tabular data is shown in Fig. 2-2, together with a faired curve depicting the relationship between work interval and maximum sustainable constant metabolic rate. This data is based upon average males 30 to 40 years of age; and, Lehmann has assumed an "optimal" work/rest cycle, namely: 8 hours of work per work day, 26 work days per month (six work days per week), but only 280 work days per year (i.e., 33 "vacation" days in addition to the one rest day per week). The shape of the curve is similar to that of the static load vs endurance curve in Fig. 2-1; but the time scale is much greater, indicating that the decrease in work capacity with increasing work intervals is more gradual.

With this number of data points we were able to fit a third-order, least-squared-error, equation to this data:

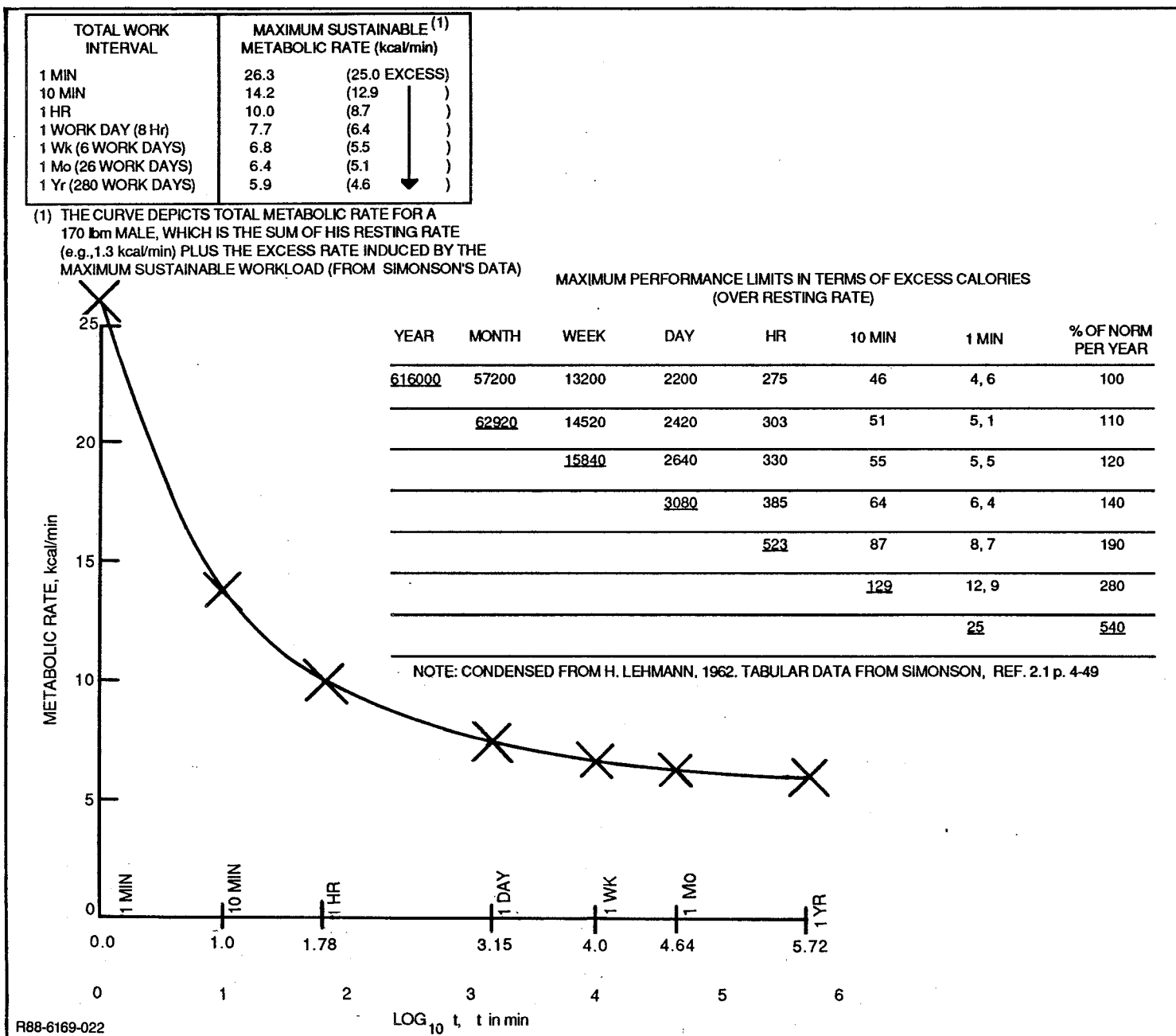


Fig. 2-2 Maximum Sustainable Metabolic Rate as a Function of Total Work Interval

$$M = 26.06 - 14.72(\log t) + 3.73(\log t)^2 - 0.31(\log t)^3 \quad \text{Eq. 2.2}$$

where:

M = Maximum sustainable metabolic rate in (kcal/min) for a work interval of duration t (minutes)

t = Work interval duration (minutes)

This equation has a calculated least squared error accuracy of 99.8%, but is not as uniformly close to each data point as is the "faired curve" in Fig. 2-2. The equation is a convenient way to obtain metabolic rate data that is accurate to about ± 0.6 kcal/min for values of t from 1 minute to 525,600 minutes (1 year).

It should be noted that the metabolic rates obtained from either the figure or the equation pertain to the work period only (i.e., 8 hours per work day, 26 work days per month, etc). Cumulative energy values obtained from these rates do not include the energy expended during nonworking intervals (i.e., the 16 hours per day spent in normal off-duty activities such as recreation, meals, hygiene, and sleep), or the nonworking days. Thus if one is calculating the cumulative metabolic output during work for a calendar interval, the rate for that interval must be multiplied by the actual working time in minutes, not the calendar time. Furthermore, if one is interested in the life support system requirements for a calendar interval, one must add the metabolic expenditures for the nonworking time to those generated during the actual working time. Table 2-1 shows the results of such calculations for the specific work intervals defined in Lehmann's data (e.g., the values in the tabular array in Fig. 2-2).

Note also that not all of metabolic output during work actually contributes to the performance of the external task, because (for our average 170-lbm male) 1.3 kcal/min are required to support the basic metabolic processes of life. Only the excess metabolic rate (above this "resting" level) actually contributes to productive work capacity. Thus, the actual work output for these calendar periods is as indicated in Table 2-2.

Table 2-1 Cumulative Metabolic Output Following Lehmann Work Protocol

Total Calendar Clock Interval	Actual Working Time	Lehmann Maximum Work Rate (kcal/min)	Non Working Time Metabolic Rate Assumed to be 1.3 (kcal/min)	Cumulative Metabolic Output (kcal)		
				During Work	During Non Work	Total
1 min	1 min	26.3	0	26.3	0	26.3
10 min	10 min	14.2	0	142	0	142
1 hr (60 min)	1 hr (60 min)	10.0	0	600	0	600
1 day (1,440 min)	8 hr 480 min	7.7	16 hr (960 min)	3,696	1,248	4,944
1 week (10,080 min)	6 days (8 hr/day) (2,880 min)	6.8	120 hr (7,200 min)	19,584	9,360	28,944
1 mo (30.4 days) (43,800 min)	26 days (8 hr/day) (12,480 min)	6.4	522 hr (31,320 min)	79,872	40,716	120,588
1 yr (365 days) (525,600 min)	280 days (8 hr/day) (134,400 min)	5.9	6,520 hr (391,200 min)	792,960	508,560	1,301,520
R88-6169-051						(From: Lehmann)

(As a check, the productive output figures should equal the underlined values in the tabular data in Fig. 2-2; and they do within the limits of the accuracy of the data.)

The work capacity depicted in Fig. 2-2 is called "whole body" work by Simonson (and Lehmann), meaning that the tasks were such that the load was distributed among the muscles in the arms, legs and torso. Other research has shown that maximum oxygen uptake associated with "pure arm and hand" work does not exceed 70% of that attainable with maximum leg work. This result is attributed to the fact that the demand in both situations is limited by muscle mass, and of course leg muscles are larger. Maximum combined arm and leg work (e.g., whole body) how-

Table 2-2 Productive Work Output Following Lehmann Protocol

Total Calendar/ Clock Interval	Actual Working Time	Excess (Productive) Metabolic Rate (kcal/ min)	Productive Work Output (kcal)
1 min	1 min	25.0	25
10 min	10 min	12.9	129
1 hr	1 hr	8.7	522
(60 min)	60 min		
1 day	8 hr	6.4	3,072
(1,440 min)	(480 min)		
1 wk	6 days	5.5	15,840
(10,080 min)	(2,880 min)		
1 mo	26 days	5.1	63,648
(43,800 min)	(12,480 min)		
1 yr	280 days	4.6	618,240
(525,600 min)	(134,400 min)		
R88-6169-052			(From: Lehmann)

ever does not equal the sum of the maximum values of the two components. In fact maximum oxygen uptake during whole body work only slightly exceeds the oxygen uptake during maximal leg work alone, "and hence the limiting factor" (for whole body work) "seems to be the capacity of the whole oxygen transporting system" [2, p. 42.5].

The final caveat regarding Lehmann's results is that his limits do not represent the absolute maximum work a human could perform in a specified interval, but rather the maximum constant work rate that can be sustained without excessive fatigue. This can be seen clearly in Fig. 2-3, where metabolic rate data associated with selected physical activities is superimposed on a graph of the Lehmann curve. (Note that the horizontal axis in Fig. 2-3 is linear and the duration is limited to 8 hours.)

The data in Fig. 2-3 raises several questions. First, it is clear that moderately conditioned individuals can exceed the "sustained maximum" level defined by Lehmann for significant intervals of time. For example, a typical jogger can sustain a metabolic rate one and one-half times the "Lehmann maximum" for more than a half hour. Marching soldiers can exceed the Lehmann limits by 20% for 2 hours or more. World

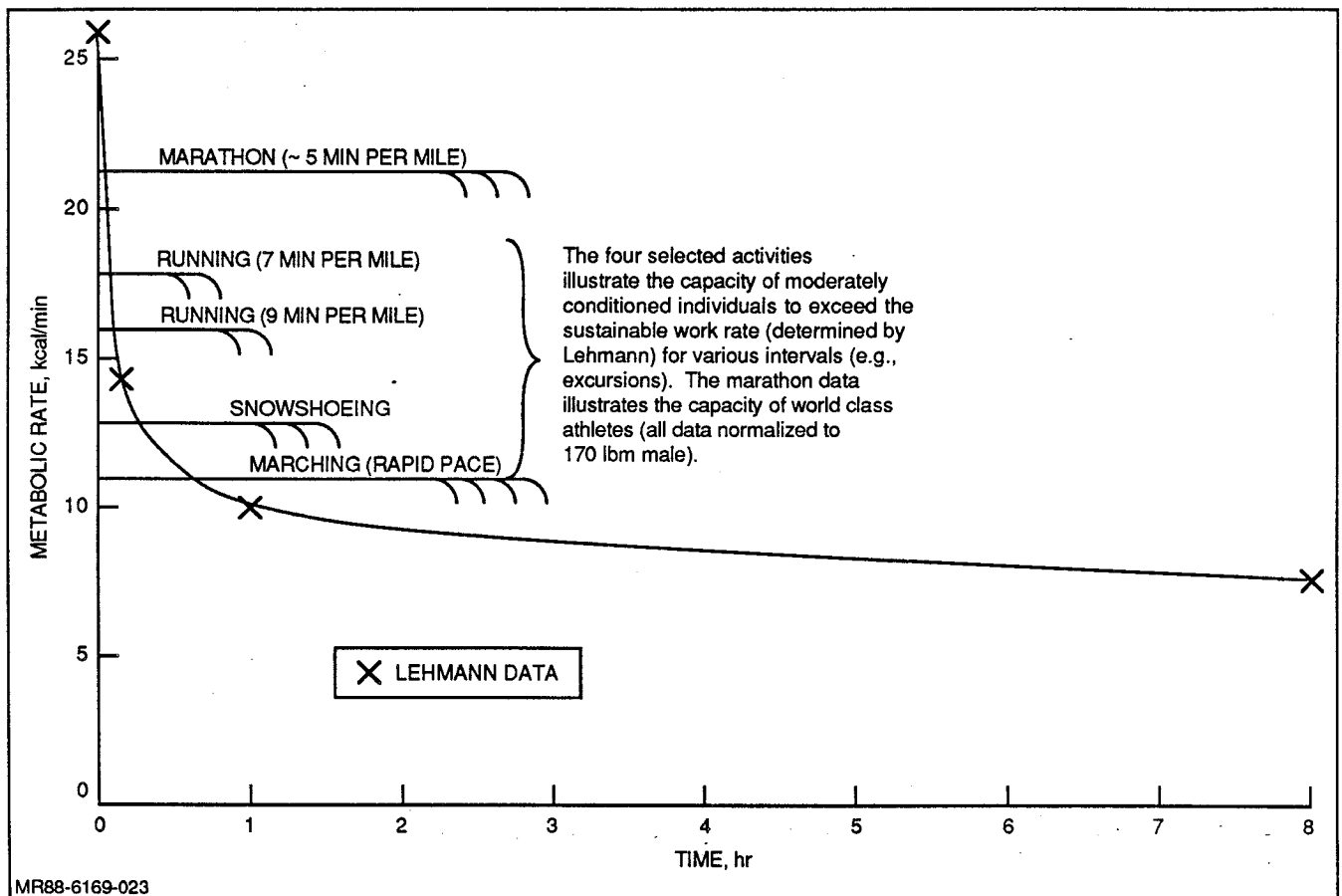


Fig. 2-3 Metabolic Rates for Selected Physical Activities Superimposed on the Lehmann Work-Capacity Curve to Illustrate the Magnitude of Possible Excursions

class marathoners have more than doubled the "Lehmann maximum" for intervals of 2 1/2 hours. Simonson [1, p. 449] states that "Lehmann is aware, of course, that an even distribution of work time and effort over the longer intervals is neither realistic nor necessary for the validity of the proposed limit," and he adds that excursions are "permissible...provided that they are compensated by periods with less intense work." Unfortunately, these "compensation intervals" are not specifically defined in terms of allowable metabolic rates or duration.

Simonson implies that the sustainable long term cumulative average work level cannot exceed the values defined by Lehmann; or alternatively, for "long" intervals, the total energy expenditure is limited to the product of the interval duration multiplied by the Lehmann limit for that interval. Hence, one could conclude that any excursion above the Lehmann curve must be followed by an interval of reduced output that is sufficiently long to bring the cumulative (integral) energy expenditure

back to within the limit defined by Lehmann. If we apply this logic to the jogger's excursion (e.g., the 9 minute per mile rate), for example, we find that the excess energy (i.e., the energy above the resting level) which would be expended during a half hour of jogging is (see Fig. 2-3):

$$\begin{aligned}\text{Excess Energy} &= (15.7 - 1.28) \text{ kcal/min} \times 30 \text{ min} \\ &= 433 \text{ kcal}\end{aligned}$$

If we now take an "accountant's" approach to the problem, we could ask how many times the jogger could perform this feat per day (or per week, or per month) for a period of one year without exceeding the cumulative energy limits defined by Lehmann. These limiting values (see the tabular insertion, Fig. 2-2) are: 2200 kcal/day, or 13,200 kcal/week, or 57,200 kcal/month. If we divide these levels by the number of calories for the "event" (e.g., 1/2 hour of jogging) that was calculated above, we find that the jogger could jog:

$$\begin{aligned}(2,200 \text{ kcal/d})/433 \text{ kcal} &= 5 \text{ times/d, or} \\ (13,200 \text{ kcal/wk})/433 \text{ kcal} &= 30 \text{ times/wk, or} \\ (57,200 \text{ kcal/mo})/433 \text{ kcal} &= 132 \text{ times/mo}\end{aligned}$$

and remain within the Lehmann limits, if he did no other physical exertion whatsoever. These calculated repetition rates seem intuitively too high, but they might be attainable under controlled conditions in which the jogger truly performed absolutely no other physical activity.

However, if we repeat this analysis for the marathoner, we find that the excess energy expended in the event is:

$$(22.3 - 1.28) \text{ kcal/min} \times 144 \text{ min} = 3026 \text{ kcal}$$

and the number of repetitions, calculated as above, would be less than once per day, or:

$$\begin{aligned}(13,200 \text{ kcal/min})/3,026 \text{ kcal} &= 4 \text{ times/wk, or} \\ (57,200 \text{ kcal/mo})/3,026 \text{ kcal} &= 19 \text{ times/mo}\end{aligned}$$

These results are simply not credible (marathon runners cannot compete this often). Hence, we must conclude that extreme excursions cannot be repeated as often as one would calculate by applying "accounting methods" to Lehmann's data.

Thus, Lehmann's curve is correct in the sense that it does apparently represent the maximum output capacity that can be attained without excessive fatigue for a given interval. Indeed, we can infer (though it is not stated by Simonson or Lehmann) that a worker can actually perform more total cumulative work over a long interval if he works uniformly at the Lehmann metabolic rate limit that corresponds to that interval. In other words, short duration excursions may produce more work output in a brief interval than would be possible under Lehmann's guidelines. However, the result would be excessive fatigue and slow recovery, so that ultimately a worker who adheres uniformly to the Lehmann limits will be able to perform more total work in a given period than he could attain in a sequence of excursions above and below the limits. The crux of the matter, of course, is the level of fatigue and the corresponding recovery time, and this leads to consideration of that area of physiological research which deals with the optimum choice of work rate and work/rest cycles to maximize performance.

There are numerous references in the literature which indicate that the insertion of "pauses" (brief rest periods) in a work interval can enhance performance either by significantly delaying the onset of fatigue, thereby extending the duration of the working interval, or by increasing the work rate without excessive fatigue. This technique, which is called "work/rest cycling," (or burst/pause cycling or some other combination of these terms) is merely a way to modify a subject's metabolic rate history. (The technique has found widespread use in athletic conditioning, where it is called "interval training.") To understand the work/rest cycle effect, one must understand the basic energy transfer mechanisms that operate during work (or exercise) at various levels of intensity for various time intervals. For those readers who are not familiar with these mechanisms, we suggest the discussion in Exercise Physiology by McArdle, Katch and Katch [5, pp. 103-6]. As the title suggests, the discussion addresses exercise, but the reader can substitute "work" for "exercise" and "worker" for "athlete" without loss of meaning.

From McArdle's discussion, it is clear that anaerobic energy mechanisms are very limited in terms of total output (one to three minutes of exercise depending

upon intensity), and that prolonged exercise depends upon the aerobic energy mechanisms. Specifically, McArdle et al point out that the metabolic rate during long-term exercise must be in equilibrium with the worker's oxygen consumption, and that the maximum attainable exercise (work) rate for intervals that exceed a few minutes is limited by the athlete's maximum oxygen uptake capacity ($\dot{V}O_{2\max}$). However, there are three aspects of aerobic work capacity and endurance (fatigue) that we feel require further clarification.

First is the fact that an athlete's (or worker's) aerobic capacity is not independent of the exercise (or work) interval. One could (erroneously) conclude from McArdle's dissertation that an athlete can produce whatever oxygen uptake is necessary to sustain any arbitrary workload (so long as it is less than his $\dot{V}O_{2\max}$) for any desired interval. However, the truth is that the aerobic capacity that can be sustained is very closely linked to the work interval.

In fact, the following mathematical formulation, which defines the energy expenditure that can be sustained as a function of both time and $\dot{V}O_{2\max}$ for a given subject, was defined by Bink, Bonjer, and van der Sluis in 1961 [1, p. 419].

$$A_t = \frac{(\log 5700 - \log t) A_{\max}}{3.1} \quad \text{Eq. 2.3}$$

where: t = the duration of the sustained steady work rate in minutes;

A_{\max} = the work rate (metabolic rate) equivalent to $\dot{V}O_{2\max}$ for a given subject, and

A_t = the steady work rate that can be maintained by the subject for an interval of t minutes.

The above equation is alleged to be valid for "prolonged work up to 1800 minutes" (30 hours) "...without undue fatigue," which means it should yield values comparable to the Lehmann curve if we select a value of $\dot{V}O_{2\max}$ that is appropriate for a "30- to 40-year old, average male" (the population covered by Lehmann's study). Before using this equation, however, we call the reader's attention to several features which may not be obvious:

- (1) Bink et al do not specify a work/rest schedule; in fact, continuous work periods up to 30 hours in duration are implied. We can neither verify nor refute this implication because we were unable to obtain the original published results.
- (2) The equation is a simple logarithmic function of work interval length, but human work capacity is not logarithmic, according to Lehmann (and several other authors). Consequently, this formulation probably sacrifices accuracy to some degree to achieve mathematical simplicity.
- (3) The range of applicability is limited at both the low and high end. The authors state that intervals greater than 30 hours are not covered, and a calculation reveals that values of t less than 4.5 minutes lead to values of A_t which exceed A_{\max} . We realize that it is not impossible for a subject to achieve metabolic rates that exceed his maximum aerobic capacity for short intervals, but the effort would require anaerobic processes, and hence may not fall within the range that was investigated by Bink, et al. Thus, the extrapolation of the function to values of t below 4.5 minutes or greater than 1800 minutes is probably not valid.

Despite these limitations (especially the uncertainty about work/rest cycles), it is informative to compare the values calculated from this equation with values from Lehmann's data. Figures 2-4 and 2-5 show curves of both sets of data for values of t from 5 minutes to 1800 minutes and 5 minutes to 480 minutes respectively. For these figures, we calculated an appropriate value of A_{\max} based upon a value of 3.5 liters/min for $\dot{V}O_2$ max for "average fit young men..." [2, p. 42.5] multiplied by 4.825 kcal/liter to obtain 16.9 kcal/min as the metabolic rate at maximum aerobic uptake. Inspection of Fig. 2-5 shows that results from these two sources agree within 2 kcal/min for work intervals from 5 minutes through 8 hours.

For intervals of less than 5 minutes, Lehmann's values include significant anaerobic metabolism, and hence we would expect them to exceed the aerobic capacity defined by the equation. For intervals beyond 8 hours, Lehmann's work capacity values are higher as expected because they are based upon a work/rest ratio of 1 to 2 (i.e., 8 hours of work at the metabolic rate given by the curve and 16 hours at a "nonworking" metabolic rate that includes a normal amount of sleep, meals, recre-

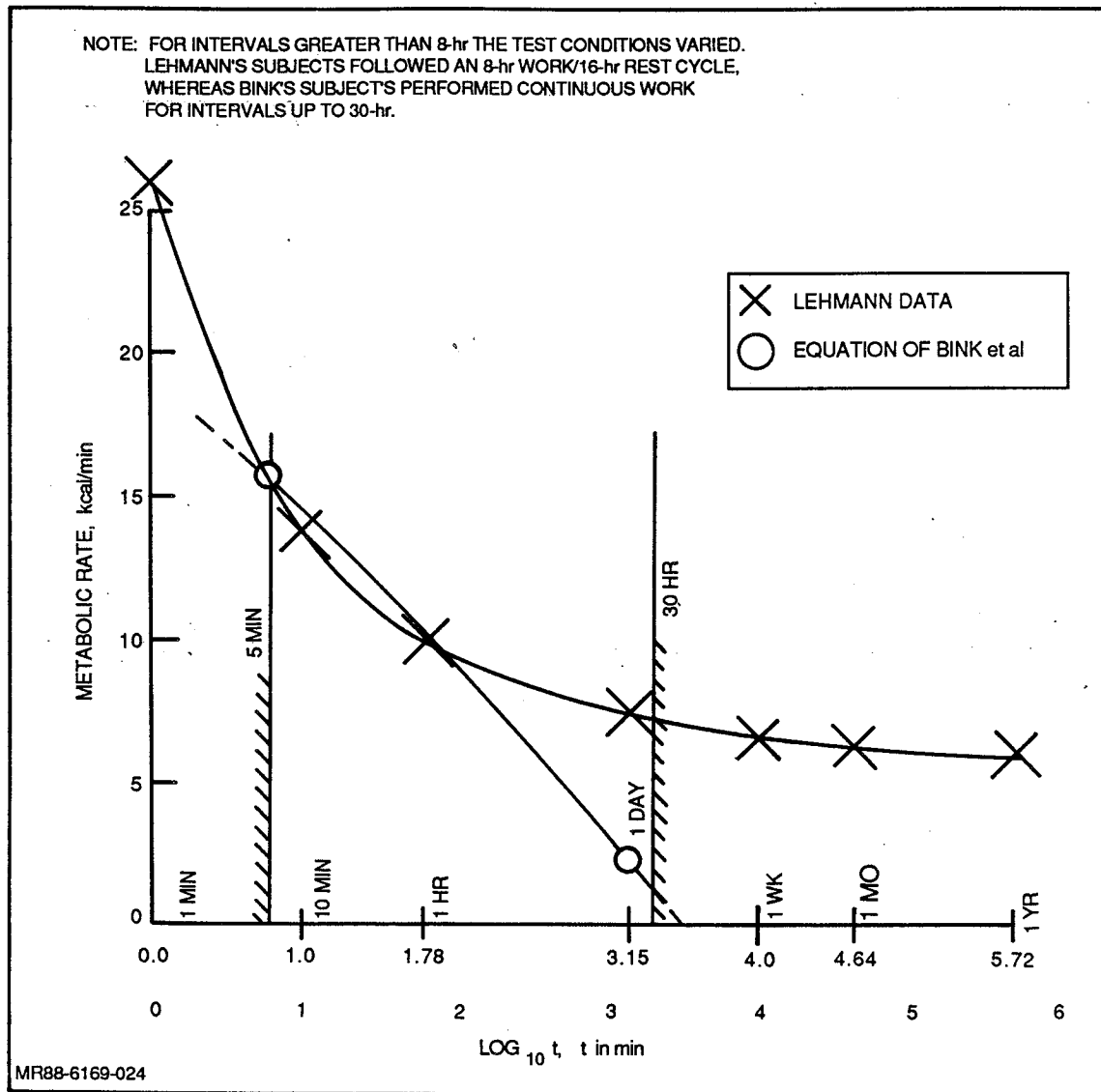


Fig. 2-4 Comparison of Work Capacity Limits of Lehmann & Bink et al for Intervals From 5 min to 30 hr (1800 min)

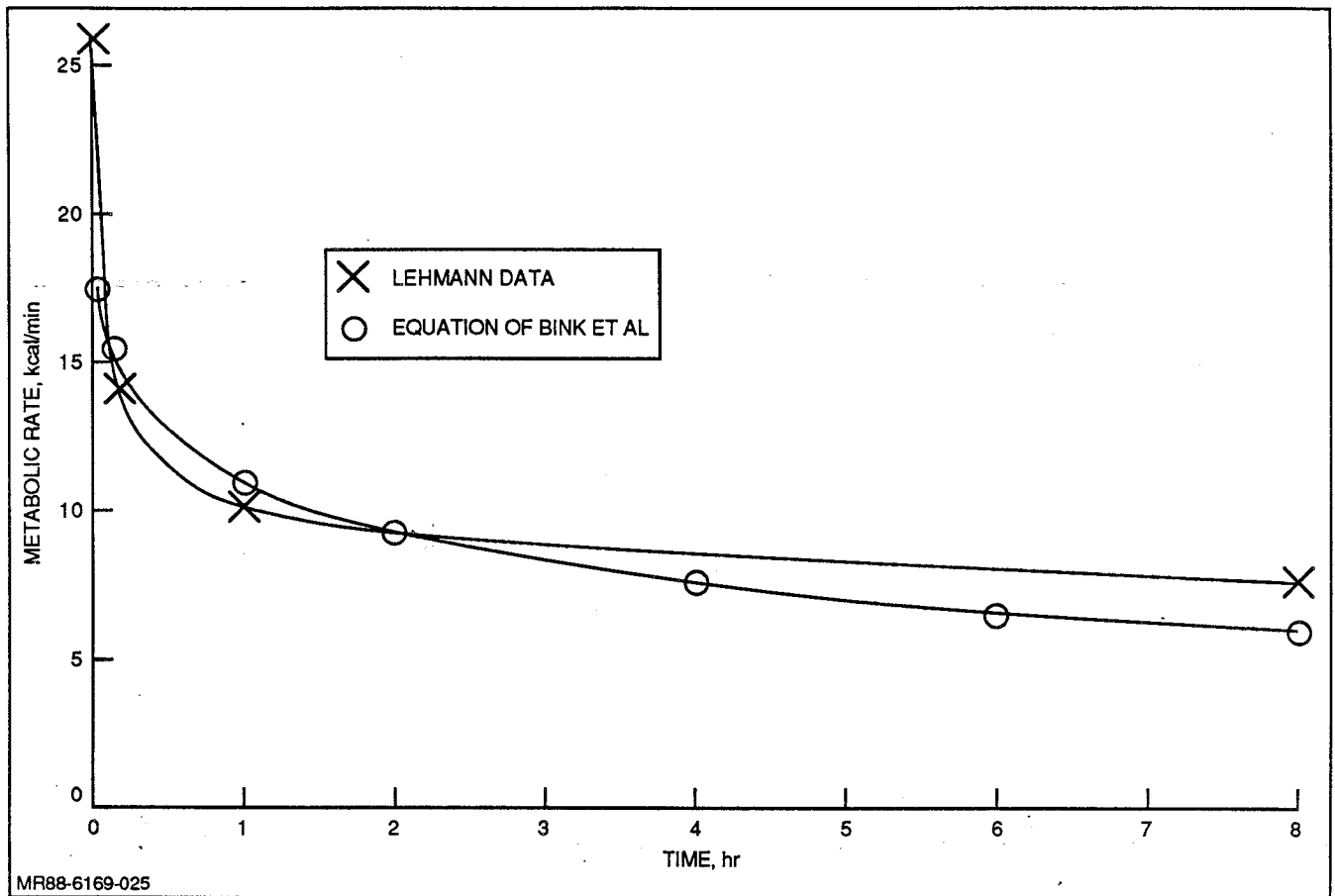


Fig. 2-5 Comparison of Work Capacity Limits of Lehmann & Bink et al for Intervals from 5 min to 8 hr

ation, etc), whereas the equation values are apparently based upon continuous work (i.e., no rest intervals).

However, it is very important to realize that if one is interested in maximizing the cumulative work output for a 24-hour interval, then a worker performing continuously at the maximum sustained aerobic rate (i.e., $A_t = 3.26$ kcal/min for $t = 24$ hours) will actually exceed the cumulative output of a worker performing for 8 hours at the Lehmann sustained rate limit (i.e., 7.8 kcal/hr) and then resting. Their cumulative work outputs will be 4,694 kcal vs 3,744 kcal respectively. Again we find that working uniformly at the maximum sustainable rate for the entire period (24 hours in this case) produces the maximum cumulative output. The implications of this result are important for an understanding of work/pause techniques, and the underlying rationale will be discussed more thoroughly during the discussion of work/rest cycles later in this subsection.

We turn now to a second aspect of long-term endurance, namely, the fatigue mechanisms. The material referenced in Exercise Physiology (McArdle et al) refers only briefly to fluid loss, electrolyte depletion, and inadequate fuel (food) as possible factors that could cause fatigue. Simonson, however, makes it clear that long-term fatigue factors, and indeed the very concept of fatigue, can be very complex; and he emphasizes that motivation can play a major role in determining the body's response to the stress of physical work. A complete description of physiological fatigue mechanisms is not necessary for our purposes, however, and we refer the reader to Simonson (Introduction and Section One) for details. Nevertheless before leaving this topic, we offer one final thought from Simonson [1, p. 441]: "...a true steady state does not exist. During prolonged work at a steady state of oxygen uptake ($\dot{V}O_2$), there is a continuing depletion of energy reserves." In short, regardless of the rate of work or the subject's aerobic capacity, any metabolic level above the resting value leads eventually to fatigue. However fuel reserves, electrolyte balance, motivation and other complex fatigue factors are not very significant for work rates within the Lehmann limits for intervals of 4 hours or less, and they are unlikely to be dominant considerations until the interval exceeds 6 or 8 hours, unless other factors such as extreme temperatures or insufficient hydration or nutrition accelerate the fatigue mechanisms.

For work intervals exceeding 8 or 10 hours, practical considerations (some of them nonphysiological in nature) may be the limiting factors. Relief from monotony, mental "fatigue," personal hygiene needs, interactive effects with other activities (requirements for coordination with other workers and associates who follow a 24-hour diurnal cycle for example), or even, for very long intervals, the requirement for sleep may dictate a halt independent of the subject's state of clinical physical fatigue. (For prolonged space operations, NASA has established a duty cycle consisting of six 24-hour work days per week, divided into two 12-hour shifts each. EVA activities should be scheduled to dovetail with this cycle insofar as possible to enhance crew coordination, minimize disruption of IVA, etc). Thus, although a worker performing 24 hours of continuous work at the metabolic rate specified by Bink et al in Equation 2.3 will exceed the work output permitted by Lehmann's limits for a 24-hour interval, he will not be able to repeat the effort for several days. A worker following appropriate limits from Lehmann's work/rest schedule can repeat the effort day after day for many months, and hence if the ultimate planned work interval is considerably greater than 24 hours, Lehmann's protocol is more optimal.

The third, and final, aspect of endurance which we want to clarify is the fact that the rapid onset of fatigue during static work cannot be explained in terms of aerobic limitations, because the metabolic rates are well within the oxygen uptake capacity of most subjects. The most widely accepted explanation seems to be that static work fatigue is a result of impaired blood flow caused by "pinching" of the vessels when muscles contract intensely. The reduced flow cannot supply oxygen or glucose nor replace muscle glycogen. The worker must depend to some degree on anaerobic energy mechanisms, and consequently develops severe localized fatigue symptoms. This rationale is also important in our interpretation of work/pause cycle effects on static work performance, which is discussed below.

For our purposes, work/pause cycles can best be treated by interpreting the results of four selected examples that illustrate the technique and its effects. Our first example is intuitive. It requires only general familiarity with a competitive athletic race of 26.2 miles called the marathon and the specific fact that running speed is monotonically related to metabolic rate [2, p. 42.5]. The example is valuable because it provides some common sense insight into the nature of the performance enhancement that can be achieved by means of work/rest cycles.

Suppose we accept as a truism the statement that "performance of work or exercise can be significantly enhanced by alternating short intervals of intense work (also called work bursts) with rest intervals (also called pauses)." If we apply this logic to the marathon, we create a dilemma. The question that arises is: "Could the marathoner perform better if he alternately ran faster than the competitive pace (i.e., faster than a $2\frac{1}{2}$ hour marathon rate) for a short interval and then rested for a short interval?" The answer is clearly "No." (If such a technique worked it would long ago have been employed under the pressure of Olympic competition.) That, in turn, leads to another question, "What is meant by the term "enhanced performance" in the context of work/pause research?"

We believe the answer is in two parts. First, one can increase the cumulative work, or exercise, output by interspersing pauses that enable the worker to perform longer. For example, a marathoner is essentially completely exhausted after the 26.2 mile race when running at a competitive pace. However, if he were allowed to rest for say 15 minutes after each 5 miles, he would be able to run farther (perhaps 35 or 40 miles or more) while sustaining his normal marathon pace during the time he is

actually running. Of course if one calculated his average speed for the total distance including the time spent resting, it would be much slower than the competitive marathon pace. Indeed, not only would the total elapsed time increase as would be expected for the increased distance, but also the elapsed time for any 26.2 mile segment would be considerably greater than his usual marathon time. Nevertheless in a sense the runner's performance has been enhanced inasmuch as he was able to run a greater distance.

For the second part of the answer, assume that the total time interval is kept the same (say $2\frac{1}{2}$ hours for the marathon runner) but bursts of intensive work (i.e., increased running speed) are interspersed with rest intervals. In this case, the runner's performance has been "enhanced" in the sense that his output rate (i.e., running speed) during the bursts would be greater than it was at the marathon pace. However, if his average speed was calculated including the rest intervals it would be less than his maximum constant sustained speed during a normal marathon. (We have not proven this last statement but it must be true; for otherwise the burst/rest technique would indeed improve on his performance for the entire marathon which is patently unreasonable.)

In summary, from this example it appears that the maximum work output in any fixed interval (or for a timed task such as a marathon) is obtained by working at the maximum constant rate which the worker can sustain over the entire interval. The substitution of burst/pause cycles in lieu of the maximum sustainable uniform rate will not increase the maximum attainable output for that fixed interval. Burst/pause techniques may increase either duration or peak intensity of work, but only at the cost of decreasing the average work rate below the maximum sustainable constant metabolic rate for the total work interval.

The second example illustrates the effect of work/pause cycles on static work performance. It is based upon results obtained by Rohmert (W. Rohmert, "Statische Haltearbeit des Menschen," Beuth Vertrid 1960 A.) as reported by Simonson [1, pp. 252-5]. Rohmert produced a very general expression that, according to Simonson; "...applies also to work durations up to eight hours and also to repeats of the same prolonged work performance on the following day"; and "...is valid for all types of static work and all muscle groups investigated and is independent also of maximum strength and sex." The expression, given below, correlates the results of many

experiments in which "different fractions of the maximum tension were maintained for different fractions of the maximum holding times, alternating with pauses of different length in order to determine the pause length which prevents any increase of pulse rate in the succeeding work periods." In other words, this equation allows one to calculate a work/rest cycle that would enable the worker to continue indefinitely (i.e., for a period exceeding 8 hours) without excessive fatigue for any static loading condition. The equation is:

$$RA = 18(t/T)^{1.4}[(k/K) - 0.15]^{0.5} \quad \text{Eq. 2.4}$$

where: RA = Rest Allowance, is the ratio of rest internal duration to the working interval duration;

t = holding time or working interval duration;

T = maximum holding time for a given subject, muscle group, and force (static load);

k = actual force; and

K = maximum force capacity (strength) of a given subject and muscle group.

Simonson also presents a graphical depiction of a sample of Rohmert's experimental results for a value of $k = 0.5 K$ for various values of t from $0.15 T$ to $0.75 T$. That data is partially reproduced in Fig. 2-6, and a specific example will be used to illustrate some of the relationships. Assume a subject with a maximum arm strength of 50 lbf holding a 25 lbf weight against gravity. (i.e., $k = 25 \text{ lbf} = 0.5 K$, as required to match the conditions in Fig. 2-6). To find T , we must use the equation in Fig. 2-1 and the selected ratio of k/K (e.g., 0.5 as stated above). We find $T = 1.1$ minutes. Now consider a working interval, t , of $0.75 T$ (yielding a value for t of 49.5 seconds) which corresponds with the upper curve in Fig. 2-6. Referring to that curve we can determine the following numerical values:

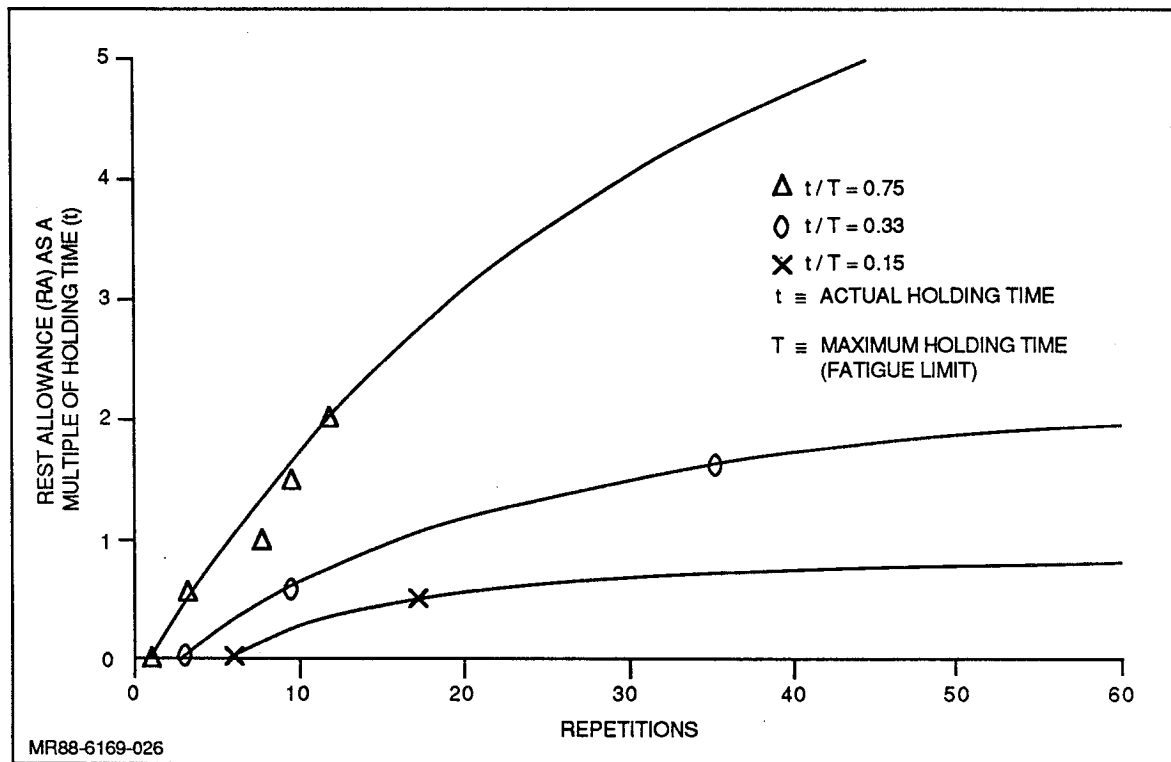


Fig. 2-6 Rest Allowance Required as a Function of the Number of Task Repetitions for Various Fractions of Maximum Holding Time. Applied Force (k) Equal Half Maximum Strength (K) for All Three Curves

- (1) For a rest interval RA equal to the working interval t (i.e., rest interval of 49.5 seconds), the worker could repeat the exercise cycle (i.e., hold for 49.5 seconds, rest for 49.5 seconds) about 6 times yielding a total duration of $6 \times (49.5 + 49.5)$ seconds or 594 seconds (9.9 minutes).
- (2) Analogously, an RA equal to 148.5 seconds (3 times the work interval) would enable 20 repetitions, and the total duration would be $20 \times (49.5 + 148.5)$ seconds or 3960 seconds (66 minutes).
- (3) For RA equal to 247.5 seconds (5 times the work interval), about 43 repetitions are possible and the total duration becomes $43 \times (49.5 + 247.5)$ seconds or 12771 seconds (212.9 minutes or 3 hours and 33 minutes).

Note in these numerical examples that cumulative holding time does not increase in proportion to total duration. In each case the cumulative holding time is given by

the number of repetitions multiplied by the holding time t (49.5 seconds for each repetition); but the total duration is equal to the number of repetitions multiplied by the sum of the holding time plus the resting time for each repetition and the percentage of resting time is rapidly increasing in succeeding cases. Numerical values are given in the following chart (times in seconds):

	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>
Cumulative	297	990	2,128.5
Holding Time		(3.3 x Case 1)	(7.2 x Case 1)
Total	594	3,960	12,771
Duration		(6.7 x Case 1)	(21.5 x Case 1)

This result confirms the intuitive conclusion that was reached in the marathon example. Total work output (measured in this example as cumulative holding time) can be increased, but only by reducing the average intensity of the work (i.e., work rate) which in this example is the ratio of holding time to total elapsed time. For the three numerical cases the average work rates are, respectively, 0.5 (297/594), 0.25 (990/3960) and 0.16 (2128.5/12271).

Finally, from Equation 2.4, the value of RA necessary to extend the work duration indefinitely (beyond 8 hours) is:

$$\begin{aligned}
 RA &= 18(.75)^{1.4}(0.5 - 0.15)^{0.5} \\
 &= 7.1 \text{ (which is beyond the limits depicted in Fig. 2-6)}
 \end{aligned}$$

In this case, the cumulative holding time would also become indefinitely long, but the average work rate would decrease even further. It can be calculated as:

$$\begin{aligned}
 \text{Avg Work Rate} &= \frac{t}{t + (RA)(t)} = \frac{49.5}{49.5 + (7.1)(49.5)} \\
 &= 0.12
 \end{aligned}$$

That is, the worker could work for a very long time, but would spend only 12% of the total time actually holding the weight.

The author did not give the metabolic rate data corresponding to these results, nor did he comment on the physiological mechanisms involved. However, he does note that holding time (with an exponent of 1.4 in the equation) has a much greater influence on the required rest interval than does load (with an exponent of 0.5). This is consistent with the interpretation of static fatigue as being a localized phenomenon caused by constricted blood flow. It can be inferred that longer holding periods produce a higher lactic acid concentration in the active muscle, and consequently a longer rest interval is required for the blood flow to restore the energy capacity of the muscle.

It seems reasonable that the use of very small holding times and the resultant increase in the frequency of rest intervals might actually change the nature of the work from static to dynamic. Blood flow interruption would be minimized, and for very short burst durations the limiting physiological factor might actually shift from "restricted blood flow" to "aerobic capacity." We found no references to this phenomenon in the literature. However if one considers the shortest holding time (e.g., 0.15 T) depicted by the lower curve in Fig. 2-6 it is clear that work rate and cumulative output are much greater. Thus, regardless of the actual mechanism, it is clear that long term sustained static performance (e.g., the product of force times the cumulative holding time) is improved as the work/rest cycle burst interval is shortened.

Our third example, taken from McArdle et al [5, p. 116], treats dynamic work in the form of running at a fixed rate (speed) and then resting for various burst/pause intervals. The results, shown in Fig. 2-7, indicate the same trend as the previous examples, and we will not belabor the reader with detailed calculation. However, one new aspect appears: In this case both the duration of the total work period and the burst work rate were fixed. Their values respectively were 30 minutes and (5.6 liters/min x 4.83 kcal/liter) 27 kcal/min. The burst and pause intervals were then varied, and it is clear from the figure that for these specific constraints, the higher of the three burst-to-pause ratios produced more cumulative work.

To analyze this result further we will use the author's statement that the selected speed (burst rate) was chosen because it represented the subject's maximum sustained 5-minute aerobic capacity. Now, if we calculate A_t for 5 minutes and for

Exercise-Rest Periods	Total Distance Run (yd)	Average Oxygen Consumption (liters/min)
4 min continuous (Baseline)	1422	5.6
10 sec exercise Test 1		
5 sec rest	7294	5.1
10 sec exercise Test 2		
10 sec rest	5468	4.4
15 sec exercise Test 3		
30 sec rest	3642	3.6

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Fig. 2-7 Variations in Running Performance for Various Work/Rest Intervals; with the Same Burst Work Intensity (27 kcal/min) and Total Work Period (30 min) during All Test Runs

30 minutes from equation 2.3 we obtain $A_t = .986 A_{\max}$ for $t = 5$ minutes and $A_t = .735 A_{\max}$ for $t = 30$ minutes. The ratio of these values is:

$$\frac{A_t(30)}{A_t(5)}$$

In words, this says that the maximum constant aerobic rate that a man can sustain for 30 minutes is about 75% of the rate that he can sustain for 5 minutes. Consequently, we would expect the "optimum" average work rate using burst/pause techniques for a 30 minute interval to be about 75% of the worker's 5 minute rate. This result is in agreement with the data in Fig. 2-7. The 10-second-exercise/5-second-rest protocol that produced the highest total work output (i.e., total distance) results in an average work rate of about

$$\text{Avg Work Rate} = \frac{(1/6 \text{ min})(27 \text{ kcal/min}) + (1/12 \text{ min})(1.3 \text{ kcal/min})}{(3/12) \text{ min}}$$

$$= 18.4 \text{ kcal/min}$$

where: 1.3 kcal/min represents the resting workload.

This average work rate (induced by the 2 to 1 burst/pause cycle) is 68% of the 5-minute aerobic capacity of this subject (27 kcal/min). In other words, a

burst-to-pause ratio of 2 to 1 is very close to the value we would select as optimal based upon Equation 2.3 for continuous maximum aerobic effort for 30 minutes for this particular test subject.

One way of interpreting this experiment is to consider the bursts as mini-excursions above the aerobic 30 minute work rate (the maximum sustainable aerobic capacity for 30 minutes) which are then "averaged out" with pause intervals of sufficient length to bring the average work rate below the maximum sustainable 30 minute aerobic capacity. Again we note that none of the burst/pause intervals resulted in performance that was as good as the performance which could theoretically be obtained by working at a constant rate of $(0.75 \times 27 \text{ kcal/min})$ 20.25 kcal/min, which is the optimum constant rate obtained from Equation 2.3. While this is not a proof, it is consistent with our belief that maximum total work can only be attained by working uniformly at the maximum sustainable constant rate for whatever total interval is selected. We have found no examples in which work/rest techniques have improved upon the limits decreed by Lehmann (or alternatively by Bink et al in Equation 2.3) for a predetermined interval.

In other words, working at the maximum constant rate for a given interval, without any excursions, seems to produce the maximum total work. Our final example further supports this conclusion. In this example from Asmussen [2, p. 42.7], subjects performed dynamic work, and the burst-to-pause ratio was held constant at 1-to-4, but the cycle time (burst plus pause) was varied in each of three 30 minute sessions, giving burst/pause times of 60 sec/240 sec, 30 sec/120 sec, and 10 sec/40 sec. In each 30-minute session the total work was 15,120 kilopond meters. A kilopond meter is equivalent to 2.34 calories, hence the average work rate was $(15,120 \times 2.34 / 30)$ 1.18 kcal/min. This of course is "external" work (i.e., measured on an exercycle or weight machine), and since the body is only about 20% efficient, the equivalent average excess metabolic rate (i.e., metabolic rate above the resting rate) is about $(1.18 / .2) = 5.9$ kcal/min and the average total metabolic rate (assuming 1.3 kcal/min as the resting rate) is about 7.2 kcal/min. The burst work rate would have to be 5 times higher, because (with a 1-to-4 burst-to-pause ratio) the worker is only working 20% of the total time. Thus the burst work rate would be 36 kcal/min, and this implies a corresponding oxygen consumption of 7.4 liters/min if the worker were at aerobic equilibrium. In fact, this consumption rate exceeds the aerobic capacity of most world-class endurance athletes, and hence we can conclude

that a substantial fraction of the effort during the burst interval is being supported by anaerobic mechanisms.

The results of the sessions in terms of blood lactate concentration vs time are shown in Fig. 2-8. Asmussen concludes that, "If a task ...is performed in short bursts of high intensity rather than at a constant rate, the same amount of work can be performed with much less strain." We would interpret these results to mean just the opposite. That is the metabolic rate during the burst is excessive; it constitutes an excursion of considerable magnitude. However, the average metabolic rate, 7.2 kcal/min, is well within the capacity of an average worker for a 30-minute interval. Consequently, an average worker working at a constant rate of 7.2 kcal/min could accomplish 15,120 kilopond meters of total work with minimal fatigue. Indeed, in this scenario, fatigue (which is equated to lactic acid concentration by this

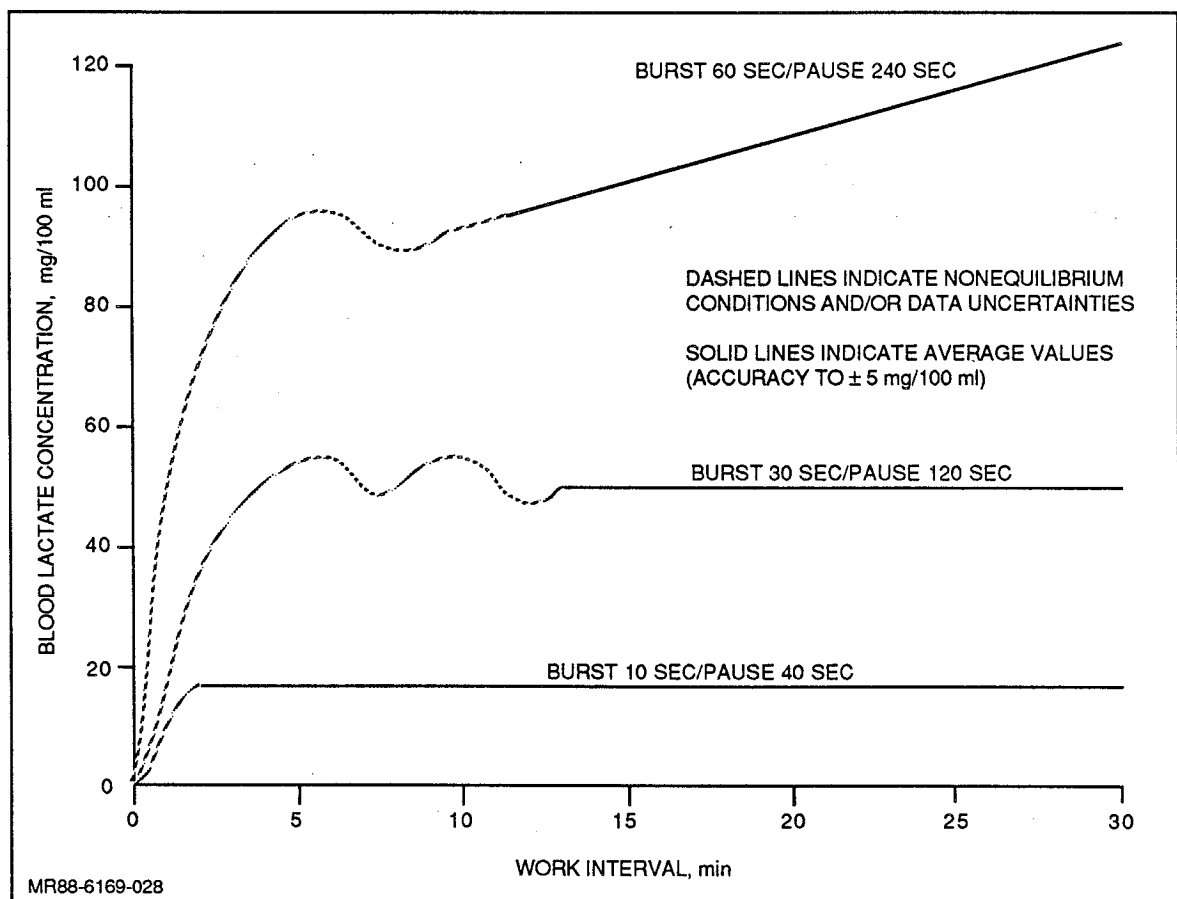


Fig. 2-8 Blood Lactate Concentration During 30 min total Work Intervals for Various Burst/Pause Intervals. Total Work (15, 120 Kpm) & Burst to Pause Ratio (1:4) The Same During all Sessions

author) is incurred precisely because the work is compressed into high intensity bursts, and the longer the burst continues at this excessive metabolic rate, the greater will be the resultant "stress" (fatigue as indicated by blood lactate concentration).

The fact that the fatigue is less (e.g., the lactate concentration is less) when the burst-plus-pause cycle time is reduced is a result of the fact that the excursion is less. The burst is "averaged out" before it can create high levels of lactate concentration. In effect, the shorter cycle duration is "homogenizing" the metabolic load; and if one could proceed to a limit in which the cycle time were infinitesimal, the net effect would be that the body would perceive the demand as a constant load of 7.2 kcal/min rather than as a series of excursions. The effort would then be less fatiguing (not more, as the author states), because the burst/pause nature of the load would be completely averaged out and the metabolic rate would approach a constant value of 7.2 kcal/min without excursions.

Obviously our literature search on basic physiological work capacity and the effects of work/rest cycles is not all inclusive. Consequently we cannot make absolute statements, but we would summarize our findings as follows:

- (1) The work rate vs endurance relationships derived by W. Rohmert (Fig. 2-1 and 2-6 and Equation 2.4) for static work, and by G. Lehmann (Fig. 2-2) and Bink et al (Fig. 2-4 and 2-5 and Equation 2.3) for dynamic work are valid statements of the maximum work rate that can be sustained for the specified intervals by average workers without excessive fatigue.
- (2) Work/rest cycles can "enhance" performance by either extending the total work interval or enabling short bursts of intense work rate, but only at the expense of reducing the average work rate below the values set by the references in item (1) above for the specified total work interval.

Conclusion 2, above, does not mean that work/rest cycles are not advantageous in some circumstances. Indeed for intervals greater than 8 or 10 hours, continuous work may be impractical because of requirements for hygiene, sustenance, relief from monotony, coordination with co-workers, and ultimately sleep. Even for shorter intervals, rest breaks may improve productivity or quality even though clinical

physiological fatigue is not a factor. However, if the intent is to achieve the maximum possible cumulative metabolic energy output for any period up to 30 hours (using the results of Bink et al), the optimum strategy is to work continuously at the highest constant metabolic rate that can be sustained uniformly over the entire interval, and the most valid sources of information to define these limiting rates are the references stated in Conclusion 1.

All of the discussion to this point has focused almost exclusively on "average" subjects performing "laboratory" tasks; and nothing has been said about the characteristics of the worker population, the nature of the tasks, or the environmental conditions. However such factors can be extremely important. In fact, Simonson presents a list of 32 factors that he considers important influences on work capacity [1, p. 325]. We have compiled an analogous list of factors which are pertinent to EVA, as shown in Fig. 2-9. However, the scope of this study precludes a thorough analysis of all these factors; only selected topics are addressed.

Categories of Factors		
Environmental(1)	Population	Task Structure
Vacuum/Suit Pressure Zero Gravity Restraints Oxygen Concentration Carbon Dioxide Concentration Temperature/Humidity Radiation	Age Sex Size (Body Mass) Condition & Health Acclimatization/Adaptation Nutrition & Hydration Motivation Training Emotional Stability	Total Job Duration Average Work Rate Complexity Task Sequence Repetition/Monotony Physical Demands: <ul style="list-style-type: none"> • Strength • Dexterity • Tactility • Hand/Eye Coordination Work/Rest Parameters: <ul style="list-style-type: none"> • Cycle Duration • Burst-to-Pause Ratio • Burst Work Rate Mental Demands <ul style="list-style-type: none"> • Detection • Recognition • Discrimination • Perception/Interpretation • Diagnostics • Creativity/Ingenuity
(1) Environmental Factors Include the Effects of the Necessary Support Equipment (Pressure Suit, Restraints, etc).		
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Fig. 2-9 EVA Work Influence Factors

In the following two subsections we discuss briefly the characteristics of the astronaut population, and, in a generic sense, the nature of EVA tasks. We believe that many of the environmental factors can (indeed must) be maintained within satisfactory bounds by the artificial environment system within the confines of the pressure suit, and hence our discussion of them is limited for the most part to an analysis of the resultant demands that are imposed on the life support system. We emphasize two factors - vacuum and "zero gravity" - which are major EVA considerations, that (obviously) are not in Simonson's list. Other sections of this study present our analysis of nutrition and hydration (Section 3.0), oxygen concentration and pressure (Section 4), carbon dioxide levels (Section 5), repeated decompression effects (Section 6) and thermal balance (Section 7).

With the exception of these specific subjects however, our discussion of worker characteristics, environmental conditions, and task factors is quite abbreviated. Consequently we feel that further study of these factors, including their combinative effects, is certainly warranted. In the following subsection we present a brief analysis of key EVA work influence factors.

2.3 EVA WORK INFLUENCE FACTORS

The material in this section is organized into four topical areas: the first, Physiologic Adaptation, addresses long term effects; and the other three, Astronaut Population Considerations, Space Environmental Factors, and EVA Task Structure, address real time elements that affect work capacity. To cope with the vast amount of diverse information in these areas, we have chosen to focus on the resultant generic effects of these factors on static and dynamic work output and endurance. Where possible, we have also suggested ground rules and methods to assess these effects quantitatively so that they may be properly accommodated in EVA work planning (procedures and timelines) and equipment design.

2.3.1 Physiological Adaptation

Absolute answers concerning the long term effects of space flight on work capacity are not available, especially for the unique conditions associated with multiple EVA. The data from U.S. space missions, particularly Skylab in which succeeding crews experienced 28, 61 and 84 days of orbital flight, indicate that inflight work capacity (as measured by exercise tolerance) is not diminished [6]. Some loss of capacity was observed postflight, and it was attributed primarily to decreased

blood volume. However, the conditions associated with long-term space exposure of astronauts (and cosmonauts for that matter) are those that exist in the cabin of the spacecraft, and they differ significantly from the EVA environment in several, potentially important, features:

- (1) Cabin oxygen pressures have never exceeded 5 psi, and in Skylab, Shuttle, and all Russian spacecraft, the cabin atmospheres have contained about 70% nitrogen as a diluent.

By contrast the Station EVA suit will contain undiluted oxygen at a pressure (proposed) of 8.3 psi.

- (2) Cabin total pressure was only 5 psi on Skylab (and earlier US spacecraft), but for the Shuttle, all recent Russian spacecraft, and the Station (as presently conceived) the cabin pressure is normally one atmosphere.

By contrast the total pressure in the EVA suit is 8.3 psi (e.g., the same as the oxygen pressure because it is a single gas system).

- (3) The intensity of physical activity, as reflected in metabolic rates, is considerably higher during EVA than during typical activities inside the cabin.

The effects of repeated exposure (3 or more times per week) to these unique EVA conditions over a period of 3 months (or longer as the station matures) have simply not been investigated. Although there is nothing to suggest any dire consequences from these conditions, there are some questions that have not been answered.

- (1) Two studies by H.A. Smedal in 1947 and 1948 [7,8], involving repeated "blind" tests of exercise effects at various hypobaric conditions with a total of 60 subjects, indicated that reduced total pressure, independent of oxygen partial pressure, led to increased fatigue (See Subsection 6.6.3 below).

- (2) Many studies (See Subsection 4.3 and references therein) indicate that no irreversible effects occur from continuous exposure to pure oxygen at pressures up to one atmosphere for periods up to a few days. Several studies also indicate that intermittent periods of breathing diluted atmospheres are beneficial in countering oxygen toxicity effects. However, there have been no definitive studies of toxicity effects from repeated exposures to undiluted oxygen at pressures of 8.3 psi for periods of 90 days or more at the EVA frequency (e.g., 3 times per week) expected on the station.
- (3) Asmussen [2, p. 42.5] states that increased oxygen concentration to 45% (a partial pressure of 6.6 psia at standard atmospheric pressure) augments oxygen uptake considerably "...and more than would be expected from the extra physically dissolved oxygen in the arterial blood." He attributes this result to an unexplained mechanism which disproportionately favors heart function. EVA astronauts, breathing pure oxygen at 8.3 psia in the suit, should experience this increased aerobic capacity and a corresponding increase in work capacity. However, this has not been observed or measured quantitatively in training or flight. Furthermore, if this "cardiac augmentation" mechanism is real, nothing is known about its long-term biomedical effects in combination with repeated episodes of high intensity workloads.

The combined effects of these and other long-term factors unique to the EVA environment, cannot be quantified without considerable further research. This is an obvious area where further study is strongly recommended.

Perhaps the fundamental question with regard specifically to work capacity is whether adaptation to the space environment can be treated conceptually as merely a change in parameter values (e.g., strength, aerobic capacity, etc.) or whether the basic mechanisms of physiological energy transfer and fatigue are actually altered in some fundamental way. If the effects are parametric in nature, then the guidelines defined in Subsection 2.2 above can be modified very simply by "scaling" in the same way that they are adjusted to accommodate the differences between one subject and another or one population and another. (This procedure is discussed below in Subsection 2.3.2.) On the other hand, if there are long-term fundamental changes in physiological mechanisms, then guidelines based on research in normal-atmosphere,

normal-gravity conditions may be totally invalid, and new formulations may be required. Based upon the evidence that is currently available, we believe the use of parametric scaling is valid at least for intervals of 90 days; and lacking evidence to the contrary we will use it in the remainder of this report as the basis for quantitative conclusions regarding work capacity.

2.3.2 Astronaut Population Considerations

Astronauts as a group are better conditioned physically than the "average" group of individuals with the same distribution of age, physical size, etc. Consequently, the guidelines on work capacity (work rate and endurance) and work/rest techniques, which were compiled in Subsection 2.2, must be "scaled up" to be valid for EVA task (workload) planning or as a basis for EVA equipment performance specification.

Fortunately, the provisions for "scaling" have already been included in the formulations to some degree. In Fig. 2-1, the load data has been normalized by expressing it as a percentage of the maximum strength for each test subject and muscle group, and the resulting relation (the curve and equation) can be applied to any worker or muscle group whose maximum strength is known. Likewise Rohmert's formulation of work/rest data (Equation 2.4 and Fig. 2-6) is generally applicable if the maximum strength of the individual/muscle group is incorporated in the parameter K in Equation 2.4. The expression of aerobic capacity derived by Bink, et al (Equation 2.3 and Fig. 2-4 and 2-5) also explicitly contains a scaling factor (A_{\max} = metabolic rate at $\dot{V}O_{2\max}$). Unfortunately, Simonson does not discuss any method for scaling Lehmann's data for different populations. However, the physiological limiting factors and fatigue mechanisms are believed to be the same as those involved in Bink's formulation for the intervals of primary interest (i.e., up to 8-10 hours of uninterrupted work). Consequently since Bink's scale factor is linear it seems logical that linear scaling based upon the ratio of aerobic capacities for the two populations (i.e., the "new" population and the Lehmann study population), would yield sufficiently accurate results. The "least squared error" curve fit to Lehmann's data (Equation 2.2) could easily be modified to contain a linear scale factor.

To apply the scaling methods to the astronaut EVA cadre, one would have to obtain measurements of muscle strength (for the muscle groups of interest) and aerobic capacity. We did not seek complete medical records because of the constraints of the privacy laws, but we did obtain values of average and maximum

aerobic capacity for the astronauts as a group. The values were 49 ml/Kgm-min and 63 ml/Kgm-min [9]. A reasonable value for the "average" subject (i.e., the basic subject in the Lehmann or Bink populations) is about 40 ml/Kgm-min, and hence the ratios would be about 1.2 for the average of the astronaut population to this average subject, or about 1.6 for the maximum measured value within the astronaut population. We did not obtain the minimum value, but the females in the astronaut office ranged from 36 to 39 ml/Kgm-min, which yields a ratio close to 1. Based on these values, the appropriate values of the population scaling factor would range from 1.6 to 1.0. We emphasize that these values are not statistically validated nor do they reflect long term demographic trend effects. They are raw measured values for the astronaut population circa 1987 [9].

Of course, EVA tasks and equipment (with the exception of suit sizing) cannot, as a practical matter, be designed to the needs of each astronaut individually. Thus, it will be necessary to define averages and bounds (statistical measures of variation) for the population as a group. Furthermore, the statistical description of the population should allow for demographic changes in the EVA cadre. To assure that this statistical database is used appropriately, we have identified two ground rules which we feel should apply in all cases:

- (1) EVA equipment should satisfy the greatest credible demands that any astronaut is physiologically capable of creating. That is, EVA performance should be limited only by the capacity of the crew members, not by some lesser capacity dictated by systems limitations. Of course, the equipment must also provide margins of safety to accommodate both degraded operational modes (i.e., equipment malfunction) and the extremely high metabolic loads that might be generated by an astronaut in response to an emergency situation.
- (2) EVA tasks should be structured such that (a) peak strength and maximal aerobic capacity demands can be met by the "weakest" EVA crew member, and (b) planned work rate and duration should be based upon the relationships in Fig. 2-1, 2-2, 2-4, 2-5 and 2-6, scaled to these "weakest crew member" maxima. This ground rule assures that any task can be performed by any crew member, and is essential for conservative timeline planning (unless one is willing to screen the astronaut EVA cadre and

"match" individuals to flight assignments - a practice that has been rejected by the Astronaut Office).

2.3.3 Space Environmental Factors

Two factors - vacuum (and the concomitant pressure suit and Portable Life Support System) and zero-gravity - are the dominant factors that differentiate the space environment from more customary human working environments. Their influence on work capacity is discussed below:

2.3.3.1 Vacuum - The effects of the vacuum environment are predominantly indirect; they derive from the pressure suit and its systems, which must provide a total artificial environment. The requirements on the suit/systems include the following:

- Artificial atmosphere for both pressurization and oxygen supply
- Thermal (heating/cooling) and humidity control
- Forced circulation devices for air in the suit enclosure and water in the liquid cooled garment worn by the astronaut
- Carbon dioxide removal
- Thermal insulation from contact with extremely hot or cold objects (+250°F, -150°F)
- Interfaces for mobility and restraint systems
- Physical protection from sharp or abrasive objects
- Nutrition, hydration and waste handling capabilities (rudimentary, but essential)
- Communications
- Radiation and micrometeorite shielding
- Protection from contamination (propellants, coolants, etc) from spacecraft/satellite systems during servicing or maintenance.

The capability of the suit/systems to provide these functions determines the operational range of the external environmental conditions that can be tolerated and the range of metabolic demands that can be satisfied. In particular, system performance requirements for the first four functions can be determined in terms of external physiological workload by means of known relations between external workload and total metabolic rates (e.g., physiological efficiency) and in turn between metabolic rate and oxygen consumption, carbon dioxide and water vapor production, and physiological heat generation. These calculations are performed in the following section using the existing database.

Unfortunately, the design and construction of the suit to meet these demands (and provide margins for safety and reliability) make it cumbersome. The thickness of material and the differential pressure make it bulky and rigid. The wearer's tactility, dexterity, range of motion, mobility, and field of view are degraded. The suit resists wearer movements, imposing extra forces and torques and requiring extra work (true physics work), in addition to the demands imposed by the productive EVA tasks. However, quantitative data on the force, torque, and (physics) work effects of the suit is, at best, sketchy and sometimes inconsistent. (Indeed, Volume II of this study presents the results of a series of pressure glove experiments which to our knowledge are the first attempts to perform statistically meaningful, quantitative assessments of these effects.) Nevertheless, using the data and relationships from Subsection 2.2 above, it is not difficult to illustrate the potential impact of suit encumbrances on the productive work capacity of the wearer.

The effects of the suit on static fatigue are illustrated in the following example. Consider an astronaut with a maximum grip strength of 50 kgf (about average for the astronauts as a group) who must grip a small diameter object (e.g., a wire or small fluid line) in his closed hand. For discussion purposes, assume that the pressure glove induces a 20% reduction in strength, and accordingly that about 10 kgf of grip force is needed to close the glove. (This estimate of glove effect is probably optimistic. Two studies [10,11], have recorded measured grip strength degradations ranging from 18% to 58% of bare-hand strength for various types of gloves, suit pressures of 4.3 psia, and different grip geometries.) With this assumption, then the astronaut's hand will (from Fig. 2-1) experience total fatigue in about 6.5 minutes, even if he is exerting essentially no force on the object itself. The time required for complete recovery of hand strength can be calculated from Equation 2.4, which gives the Rest Allowance for this case as:

$$\begin{aligned}
 \text{RA} &= \frac{\text{Rest Interval}}{6.5 \text{ (min)}} \\
 &= 18(6.5/6.5)^{1.4} [(10/50) - 0.15]^{0.5} \\
 &= 4.02
 \end{aligned}$$

Thus, the required rest interval is about 26 minutes. The impact to total productivity is obvious and surprisingly large for a task that would require no appreciable force nor induce any fatigue if it were done barehanded.

The suit effect on dynamic (physics) work is a combination of three elements: flow work, fabric work, and slip-ring work. As the names imply, slip-ring work and fabric work represent the amount of energy that goes into moving the slip ring joints and bending the fabric when the suit is moved from its neutral position (The neutral position is the position the suit assumes when pressurized in the absence of wearer or external forces or torques). The quantitative value of these terms is equal to the product of the torque required to bend the fabric and/or rotate the slip rings multiplied by the angle (in radians) of the bend from the neutral alignment. Slip ring torque is a result of friction in the bearings and thus (in theory) should be linearly proportional to suit pressure. (Friction is proportional to normal load and, in turn, "normal" load on the bearings is linearly proportional to suit pressure.) Fabric resistance is, at least in part, caused by sliding friction among the multi-layers of suit material, and thus it may also increase with suit pressure, but we found no quantitative data in the literature.

Flow work is work associated with the movement of pressurized atmosphere (oxygen in the current suits) when part of the suit is deformed during body motion, temporarily "squeezing" the atmosphere out of that part and into the remaining suit volume. The volume that is displaced is typically very small (as will be illustrated in the following example), and total suit pressure is essentially unchanged. Thus the amount of work can be calculated very accurately as the product of suit pressure multiplied by the displaced volume (the thermodynamics "constant pressure flow work" term). This work is clearly proportional to suit pressure.

The magnitude of each of these work terms is small, but they occur each time the suit is "flexed" (i.e., displaced) from its neutral position. For repeated motions, the cumulative work that is "absorbed" by the suit can be significant, as the following example shows. For illustrative purposes, the author measured the surface area of the "plan view" of his hand (by tracing the outline on a 1/4 in. grid and "counting squares"), and found it to be 24 in.². It was then assumed that the glove, when pressurized, in the neutral position contains a thin sheath of air, 1/16 in. thick, between the inner surface of the glove and the hand. (The author's

experience causes him to believe this is a conservative estimate; that is, the actual sheath thickness on the average is probably greater.) The volume of air in the sheath on the palm and back of the hand combined is then $(1/16 \times 24 \times 2) \text{ in.}^3$. If we now assume that the sheath is squeezed to 0 thickness when the hand is closed, then the amount of flow work would be $(4.3 \text{ psi} \times 3 \text{ in.}^3) = 12.9 \text{ in-lbf}$ or about 1 ft-lbf which, in calories, is about 0.3 cal. If the hand is opened and closed 30 times in one minute (for example as might be done when using a scissor-action tool or when testing on the BTE) the power required would be 0.009 kcal/min, which is about 0.5% of the total metabolic rate of a 170-lbm man sitting quietly. This is not an insignificant workload for a single hand; it amounts to 0.6 W, a sizable fraction of the author's total bare hand power capacity (as measured on the BTE) of about 4.1 W for a one minute interval.

In the glove there are no slip rings, but there would be some fabric work. If it is assumed that fabric resistance does not change with suit pressure, then the author estimates that fabric work would be less than 1/5 of the flow work based upon his qualitative assessment of a pressurized glove versus an unpressurized glove. (However, as discussed above, this term may increase with suit pressure.) In any event, whatever its magnitude, fabric work further increases the amount of energy that is absorbed by the suit, and hence further reduces the wearer's capacity for external (task productive) work and power.

Note that the examples given above are based largely on estimates, because very little quantitative, statistically valid data is available. One reason is probably the cost of multi-subject, pressurized testing. However we feel that quantitative data and methods of measurement are essential to a sound engineering understanding of suit work effects and to the objective evaluation of future suit designs. Such a database would also be of value in the development of EVA work procedures and timelines. We strongly recommend a comprehensive, systematic research effort in this technical area.

2.3.3.2 Zero Gravity - The other dominant, space-unique environmental factor is zero gravity; it deprives the astronaut of his customary means of mobility, positioning, and restraint for himself and for his tools, equipment, and supplies. To compensate, the EVA worker must either rely upon mechanical aids (e.g., tethers, foot restraints, tool caddies, the RMS, etc) for all these functions, or alternatively

substitute the use of his arms and hands. However, neither of these alternatives is compatible with the instinctive techniques of body control or physical manipulation (e.g., exertion of forces, torques, etc) that would be available in a one gravity environment.

Arm forces and torques that are reacted through fixed foot restraints, for example, may impose large, unaccustomed lateral, twisting or bending loads on ill conditioned muscle groups in knees, ankles, feet, etc. The astronaut cannot "shift his feet" or "bring his weight to bear" in this situation. For example, an astronaut pulling with one arm in a direction perpendicular to the long axis of his body with a force of 25 lbf at shoulder height can produce a bending (torque) load on his ankles of 110 ft-lb (1325 in.-lb). This load exceeds the maximum capacity of the affected ankle muscles, and requires the use of the other hand (or some other mechanism) to react the load.

Even the simple act of positioning and stabilizing one's own body or an item of equipment for a period of more than a few minutes can be extremely fatiguing if there are opposing forces or torques (including the resistance of the suit, if it is deformed from its neutral position.) Consequently, an EVA task, which would involve a relatively minor effort of a single arm and hand in a one gravity environment, may impose large, sustained loads on a variety of poorly adapted muscle groups and in turn quickly induce fatigue.

Although this is an area where little quantitative data currently exists, it is probably amenable to computer modeling techniques that could be used to generate an extensive database for EVA workload assessment and planning. (Provided, of course, that basic data on forces, torques, and timelines is available. As indicated above, the acquisition of suit data for these purposes requires additional research.) We recommend that appropriate computerized techniques be developed.

2.3.4 EVA Task Structure

The primary sources of information on EVA task structure were EVA Mission Reports, selected NASA and contractor studies [12-14, 16-23, 25, 26, 34, 35], and a few informal personal communications with EVA astronauts (primarily Jerry Ross, Woody Spring, and Bruce McCandless). We believe that four key findings can be derived from these sources:

- (1) EVA task procedures and sequencing are often dictated by nonphysiological factors and consequently are not "optimized" to enhance work capacity.
- (2) Despite the fact that average metabolic rates during EVA are well within the capacity of average 30 to 40 year old workers as shown in Fig. 2-10, astronauts consistently report experiencing fatigue.
- (3) Other than the obvious effects of the suit itself, the proper use of positioning and restraint devices is the most important single influence on productivity and fatigue.

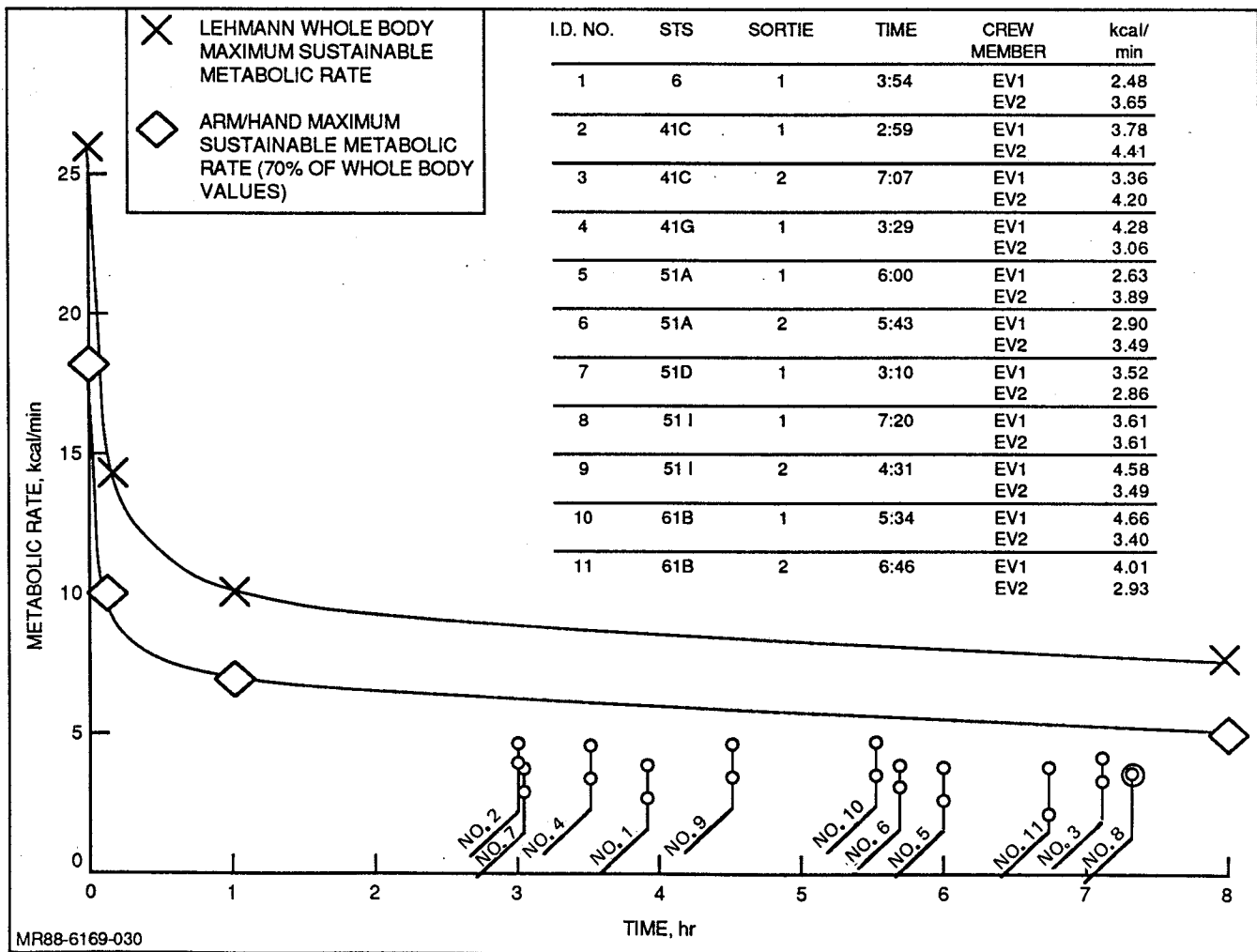


Fig. 2-10 Comparison of Actual EVA Average Metabolic Rate Data with Lehmann Sustained Maximum Work Capacity Limit Curve (Metabolic Data was not Available for STS-41B)

- (4) The amount of time that is expended for nonproductive overhead tasks (e.g., suit servicing, prebreathing, systems checks, airlock operations, translation to and from work sites, unstowing/restowing equipment, deploying restraint devices and equipment caddies, periodic systems monitoring, etc) is considerably greater in the EVA environment than is the case in most other work activities, even those involving underwater, high-altitude, or other hostile conditions (e.g., fire fighting, antarctic exploration, etc).

Each of these four elements is important in determining approaches to optimize physiological work capacity in EVA. They are discussed below.

2.3.4.1 Task Procedure & Sequencing - EVA task procedures and sequences are usually dictated by mission factors (e.g., day/night intervals, rendezvous dynamics, consumables budgets, etc) and by the mechanical design and operating principles of the devices upon which work is to be performed (e.g., a particular satellite, component or black box requires a unique prescribed set of actions and tools for restraint, access, servicing, diagnosis, repair, etc). Furthermore, current systems were not designed to facilitate EVA maintenance, servicing and repair. Although some effort is now being made to include design features in future devices which will make them more compatible with suited-astronaut capabilities and limitations (and, to accommodate robot servicing features, which incidentally are not generally incompatible with EVA requirements) they seem to be focused on "access" (e.g., sufficient clear volume for a suited astronaut to achieve a satisfactory position, and internal clearance for gloved hand manipulation) and dexterity/tactility (e.g., making the mechanical interfaces such as fasteners, latches, electrical and fluid connectors, and operating switches and knobs easy to grasp and manipulate with the pressure glove).

Apparently very little thought has been given to designing space hardware or structuring EVA tasks so as to minimize the physiological work imposed on EVA crews. One reason for this omission is the lack of quantitative data or well-formulated physiological ground rules and guide lines. Another, and very important, reason is the desire not to adversely impact other dominant design requirements (e.g., minimum weight and volume, maximum ruggedness and reliability, integrated thermal properties, etc) or cost. In any event, considerations of EVA (or

robot) compatibility were thought to be relatively unimportant in existing hardware designs because EVA (or robot) maintenance and servicing was regarded as an unlikely contingency. Now that on-orbit maintenance and servicing is becoming an accepted way of operating in space (indeed absolutely essential for the 30-year life cycle of the station), EVA (and robot) work capacity takes on increased importance. Clearly this is an area where further research is needed to correlate physiological work effects with hardware design features and EVA task procedures and timelines.

2.3.4.2 Fatigue - There is ample evidence that astronauts experience considerable fatigue during EVA. During the flight of STS 6 [12], Story Musgrave was observed to be having difficulty handling a drink container immediately after doffing the pressure suit, a fact which he attributed to extreme hand and arm fatigue (personal observation of the author). Comments from crew members on other flights also attest to fatigue. During debriefing of the crew of STS 41C [13, p.74] it was noted that "...the power screwdriver was invaluable in not only shortening the timeline but saving wear and tear on the poor crewman." This crew also suggested that EVA on consecutive days was too fatiguing to be acceptable on a routine basis, although "back to back" EVA could be performed if necessary in a contingency situation. After Flight 61B (the EASE/ACCESS EVA mission) [14], Astronauts Ross and Spring specifically stated that an EVA crewmember must pace himself so as to "not go too fast and burn out." Spring stated that his fingers and hands were "a basket case" after 4 hours, and Ross said his fingers were very tired after the first EVA. This crew confirmed that EVAs on consecutive days will require more than one EVA crew if the schedule extends "for 4 to 6 days" or longer. As a result of flight experience, the Astronaut Office has established an STS policy that precludes planned EVAs on consecutive days for a single EVA crew. A similar policy is expected for Station EVA operations.

Several crew members have also stated that 6 hours of actual work is the maximum time that is reasonable for a single sortie; but it is not clear that fatigue is the only, or even the dominant factor, in establishing this limit. Discomfort and inadequate provisions for waste collection in the suit may also have influenced crewmembers opinions. A limit of 6 hours is established for STS EVAs [15], but it is based upon life support systems capacity (specifically carbon dioxide scrubbing) and allows 30 additional minutes for airlock operations and retains a 30 minute reserve for emergencies. It should be noted that 6 hours of actual working time

equates to at least a 10-hour day for the crew, when EVA overhead time and crew habitability needs (hygiene, meals, etc) are considered.

In any event, it is clear that experienced crew members agree that fatigue is a limiting factor, and an obvious question arises as to why this is true for an activity in which metabolic rates as shown in Fig. 2-10 are quite reasonable. The answer, we think, involves a combination of three physiological factors. First, EVA work is predominately hand and arm work [16] and a subject's maximum hand/arm capacity creates only about 70% of the metabolic demand that would be generated by "whole body" work (Lehmann's data, the upper curve in Fig. 2-10 is based on "whole body" effort.) That is, a subject will experience fatigue in hand and arm muscles at a lower metabolic rate than is normally correlated with "whole body" fatigue. However, this factor alone does not account for the discrepancy in metabolic rates that is observed in Fig. 2-10; that is, if Lehmann's limits are adjusted downward (to 70% of the whole body values) they still exceed the EVA "sortie-average" energy expenditure rates by a wide margin. (See the arm/hand work capacity curve in Fig. 2-10.)

A second factor that probably contributes to the discrepancy between the laboratory data of Lehmann and Bink and EVA data is the unevenness of the work rate during actual EVA tasks. Remember that Lehmann's data and the equation of Bink et al are based on reasonably steady work rates (i.e., without extreme excursions) and we believe (based on our review of work/rest cycles) that steady work rates are more efficient (i.e., less fatiguing for a given total work output) than work at varying rates (excursions) even though the average metabolic rates may be the same.

EVA tasks do not exhibit uniformity of work intensity. For example, the capacity for whole body work for a 6-hour interval is about 8.1 kcal/min (from the upper curve in Fig. 2-10), and the corresponding capacity for hand/arm work is (70% of the whole body value) about 5.7 kcal/min. However, peak metabolic rates encountered during EVA arm/hand work often reach or exceed 9 or 10 kcal/min. We believe that excursions of this magnitude, even though they may be sustained for only a few minutes, can heighten fatigue and reduce total work capacity. Therefore it is reasonable to expect that the cumulative work capacity of EVA workers will be reduced below the values indicated by Lehmann or Bink et al. The precise quantitative effects of these excursions over the course of an EVA cannot be determined,

because the physiological relationships are not sufficiently defined; and, even if they were, the EVA physiological database is not sufficiently detailed or comprehensive. However, we feel that the lack of uniformity in work rates is a significant factor in crew fatigue, and further research is recommended.

We believe the final factor that induces a disproportionate level of fatigue during EVA is the high static work component. Certainly the physiological characteristics of static fatigue (discussed in Subsection 2.2) are consistent with the observed EVA results: namely high levels of fatigue in relatively short work intervals with low to moderate metabolic rates. Also many EVA tasks tend to impose long duration static loads. As discussed above, when working under zero gravity conditions the stabilization of the body and the retention of hand held equipment requires continuous effort, often involving seldom-used, and hence poorly conditioned, muscle groups. Precise positioning of hand-held items requires additional effort from opposing muscle groups to rigidize the body. Furthermore these loads are substantially increased if the suit must be held in a nonneutral alignment. A quick screening of several EVA video tapes confirmed that astronauts are using their hands and arms almost constantly to hold themselves in place or to restrain and position equipment, supplies and tools.

We conclude that much of the fatigue reported by astronauts is hand and arm fatigue induced by uneven work rates and sustained, high static workloads. Probably little can be done to control work rates because they may be dictated by mission timelines or hardware design. However substantial increases in work capacity might be attained if hand/arm loads, especially static loads, are reduced. In turn, quantitative measures of workload and fatigue are needed: to define the magnitude of the load and determine the specific muscle groups that are involved; to guide the design of equipment and development of procedures; and to provide accurate, comparative measures of alternatives. This is an area where the use of electromyographic techniques, applied to suited subjects during actual EVA and neutral buoyancy activities, offers significant advances. We strongly recommend that such efforts receive high priority.

Until quantitative data becomes available, we feel that the whole body work capacity limits defined by Lehmann and Bink et al must be modified to provide a reasonably conservative guideline for EVA task planning and equipment design. First,

a reduction of capacity of about 30% is required because EVA work is largely confined to hand and arm activity. Further reduction is undoubtedly needed to accommodate the heightened fatigue effects associated with (1) the unevenness of EVA work intensity and (2) the disproportionately high static component in EVA workloads. Neither the theory nor the database are sufficient to enable the derivation of a value for the overall EVA scaling factor (which we will refer to as the Task Structure Factor) from purely physiological considerations. However we obtained an empirical estimate as follows: first we formed the ratio of the value of the observed metabolic rate for each EVA with the corresponding value of maximum whole body work capacity from the curve in Fig. 2-10 for the time interval of each EVA. Then we averaged the various ratio values (one for each crewmember/sortie) to obtain an "EVA to Laboratory" scaling factor. Of course, this factor implicitly contains the population scaling factor, because the observed data represents the performance of the EVA cadre. However the population factor can be divided out; that is, the "EVA to Laboratory" factor could be divided by the "EVA Cadre-to-Average Worker" aerobic capacity ratio (as was discussed in Subsection 2.3.2 above) to obtain an estimate of the task structure factor. The value thus obtained is 0.36. This means that the metabolic work capacity of an average worker would be reduced to 36% of its normal whole body value when the worker is confronted with the structure of EVA-tasks.

This value is not very precise, of course. In addition to concerns about the small number of samples and questions about the appropriateness of averaging the individual EVA-to-Laboratory ratios, there are other reasons to challenge the validity of this number. For one thing, we are concerned in this analysis with maximum sustainable work capacity, whereas observed data represents metabolic loads induced by whatever actual tasks were performed. The results probably do not represent the sustainable maximum capacity of the crew, because EVA workloads are intentionally planned so as to leave some reserve capacity to enable crew members to cope with unexpected, high-demand contingency situations. Also, of course, a Task Structure Factor based on average EVA metabolic rates does not yield any insight into the magnitudes of possible excursions. (In fact the observed average values probably do not include the effects of a single maximum excursion, because astronauts have never been placed in extremis during STS EVAs.) Consequently, if the empirical value of the Task Structure Factor (as defined above) were used to calculate the sustainable metabolic rate that should be applied in EVA planning or equip-

ment design, it would probably yield a slight underestimation of astronaut EVA metabolic work capacity. For the purpose of EVA task timeline planning, an underestimate of capacity is conservative and hence probably acceptable. For the definition of life support system requirements, the value should be adjusted to accommodate the statistically expected variations in demands and also provide contingency reserves.

In the absence of sound physiological data, the amount by which this empirical factor should be adjusted is a matter of judgement. For short durations, (30 minutes or less) the expected EVA metabolic demand will almost certainly not exceed the maximum aerobic capacity (whole body work) of the "three sigma" male astronaut, but this value is probably overly conservative as a basis for a design specification. For example, the maximum value of measured aerobic consumption for the current astronaut population is 63 ml/kgm-min. If we assume the body mass of a three sigma male to be about 210 lbm (95 kgm) and use the standard factor of 4.825 kcal/liter to convert from aerobic uptake into energy units we obtain a metabolic rate of:

$$\frac{63(10^{-3}) \text{ liters}}{\text{kgm min}} \times 95 \text{ kgm} \times \frac{4.825 \text{ kcal}}{\text{liter}} = 28 \frac{\text{kcal}}{\text{min}}$$

Further assuming a 20% mechanical efficiency for the body, the thermal load would be (80% of the total) 22.4 kcal/min or 5331 BTU/hr.

If we use Equation 2.4 to find the corresponding value for the sustained effort of 15 minutes duration we obtain:

$$A_{15} = \frac{(\log 5700 - \log 15) 5331}{3.1} = 4436 \frac{\text{BTU}}{\text{hr}}$$

By comparison, the current STS EMU is specified to provide a "peak" thermal cooling rate of only 2000 BTU/hr for a 15 minute interval. Hence, the value obtained from $\dot{V}O_2$ max data would increase the specified peak life support system capacity by a factor of more than 2, and in turn drive weight, cost, and, possibly, volume requirements upward. On the other hand, there is no absolute guarantee that the present suit would actually meet the demand imposed by a three-sigma male astronaut in an all-out do-or-die effort. We cannot resolve this issue without more quantitative data. However, in Subsection 2.4 below we will provide estimated values based upon judgemental factors of safety.

2.3.4.3 Work Effects of Positioning & Restraint Devices - For a given task and suit design, it appears that the most important ancillary factor effecting both physiological fatigue and productivity is the proper use of positioning and restraint devices. This is confirmed by several studies. For example, a report by the Garrett Corporation [17] concludes that "...with one exception, [subjects] operated at metabolic rates of less than 8.5 kcal/min (1500 BTU/hr). In every case where the metabolic rates were relatively increased, the subjects used their restraint systems improperly." Similarly, in a series of assembly tasks [18] a comparison of task times revealed: "In tests 6 to 8, the significant improvement over tests 2 to 4 can be attributed to providing foot restraints at station C." As a final example, we note that one of the specific objectives of STS Flight 61B was to compare the relative merits of restraint and positioning devices vs "free" operations during representative (EASE/ACCESS) assembly tasks. The results, though not stated explicitly in the mission report, were made extremely clear in the crew's debriefing comments. They emphatically said that the use of restraints improved performance and simultaneously reduced fatigue [14].

Clearly, efforts to optimize EVA work capacity should investigate potential improvements in restraint and positioning devices, and it is clear from the following examples that there is room for improvement.

A very perceptive observation regarding the continuous nature of the stabilization task and the difficulty of truly rigidizing the body was made by EVA crewmember Joe Allen in response to a question during debriefing following STS 51A [19, p. 38]:

How do you feel about large mass handling with respect to space station assembly tasks?

As long as your feet are restrained, handling up to two tons should not be a problem. Allen commented that there seemed to be an inverse law taking effect: The smaller the object, the more effort it takes to control it in zero-gravity due to the microscopic forces constantly being generated on it by the astronaut. The effect of these on position matters less with increasing mass.

From this example it seems clear that in addition to restraining the astronaut, we should also consider ways to restrain and position payloads.

A second example serves to illustrate the inefficiency that is inherent in the use of fixed foot restraints. It consists of an assessment of crew workload and positioning techniques, which was taken from the STS 61-B EASE/ACCESS Mission Report [14, pp. 8-9]:

By viewing the videotapes, one can see that quite a bit of suit mobility was required for these EVAs. Due to the positioning of the two foot restraints in relation to the assembly fixture and the bar stowage assemblies, ACCESS build up and tear down required a fair amount of twisting and flexing at the waist and knees. This was minimal however compared to the dexterity required for EASE, especially in the 'low man' position. EV-1 provided the best illustration of this.

It was EV-1's task when in the lower position to stow and destow the EASE beams. As mentioned before, these beams are each 12 ft long. The foot restraint is located at their halfway point. In order to release or stow the beams, the crewman in this restraint must bend to either side. Ross chose to accomplish this in two quick motions while fully in the foot restraints. This technique involved a large amount of ankle and knee flexure, as well as significant 'bouncing' on the foot restraint. In between times Ross would usually execute one or more backbends to check on the construction, again flexing his ankles, knees and the foot restraint. When Spring had the 'low' man task, he normally chose to move more slowly and to have one foot out of the restraint. This could be because he needed more extension due to his slightly smaller stature. As far as the 'high man mobility requirements are concerned, they are much lower. Both crewman did however use their arms and legs to hold on when moving about the assembly.

This first EASE/ACCESS EVA lasted 5 hours, 34 minutes at vacuum. Average metabolic rates were 1113 BTU/hr for EV-1 and 810 BTU/hr for EV-2.

We would surmise from this example that neither crew member could sustain the static load that would have been needed to hold the suit in a non-neutral position

long enough for them to complete the task. Instead, EV-1 chose to use a "dynamic" technique, bouncing from side to side to extend his reach; and EV-2 chose to reduce the static resistance by removing one foot from the fixed restraints. (Note that EV-1 actually altered the nature of the task from "static" to "dynamic," enabling himself to exert greater energy with less fatigue, and his metabolic rate was correspondingly higher. EV-2 simply reduced the overall workload, probably at the expense of a somewhat greater static load on his ankle, knee and leg muscles.)

From the preceding example it is clear that fixed foot restraints are not ideal for some tasks. However they are clearly preferable to working unrestrained. Consequently one might ask why astronauts sometimes elect to work without restraints for themselves and their tools and equipment. We think the answer is that for some tasks fixed personal restraints may restrict reach and visibility too much, and likewise fixed equipment restraints may be too inflexible to support positioning (and repositioning) of tools and equipment as work proceeds. Occasional relocation of the restraints themselves might alleviate these problems, but the overhead time to accomplish multiple relocations of these devices is prohibitive because the mechanical attachments are time consuming to operate.

It seems apparent that a restraint device that permitted some degree of rapid, easy "local" (i.e., within a small work site volume) repositioning might be very beneficial in reducing crew work load. Of course, the RMS offers this capability and it has been used to advantage. However, it has two serious drawbacks: it can only serve one EVA crewmember at a time and it requires full time support from one IVA crew member. We recommend that NASA undertake the development of a self-contained repositionable restraint device that can be operated by an EVA astronaut without dismounting.

2.3.4.4 EVA Overhead - Although it is not, for the most part, directly related to physiological work capacity, "overhead" does significantly affect EVA productivity; and hence it must be considered in both EVA work planning and equipment design. For our purposes, there are two subcategories of EVA overhead, which we have designated as "preparatory overhead" and "coincident overhead." Preparatory overhead includes the total time required to clean, service, and maintain EVA equipment; to evaluate work requirements and plan a sortie; to review and coordinate procedures and perform any needed refresh training; and finally for actually donning/doffing EVA gear, prebreathing, systems checks, and airlock operation.

The time required for preparatory overhead is strongly affected by equipment design and operational ground rules. Automated checkout and servicing systems will reduce equipment preparation time to a minimum; increased suit pressure and/or a decision to accept increased R values (the ratio of body nitrogen pressure to suit pressure) will minimize the prebreath interval; electronic databases and computer-graphics check lists may reduce crew planning time, etc. However, certain functions will probably have to be performed manually. For example the cleaning/sterilizing of suit interiors and the inspection of the suit for rips, punctures, and abrasions will likely require dexterity and visual perceptiveness that are beyond the capability of automated systems. Refresh training and coordination are unavoidably paced by the human's capacity to communicate, learn, and understand. Certain "real time" operations such as doffing/donning, communications checks, safety checks, and airlock depress, repress and hatch operations will either be performed manually or will proceed in steps under manual control to assure proper function and safety to the satisfaction of all the crewmembers. (That is, the crew members, not the computer, must be convinced before they will proceed with actions that affect safety and mission success.) In view of these manual roles we believe that preparatory overhead will require a minimum of 4 manhours for an EVA sortie (30 minutes for suit cleaning and inspection; 30 minutes for refresh training, work planning and crew coordination; 20 minutes for donning/doffing of the waste collection device, bioinstrumentation, cooling garments, and suit; 20 minutes for airlock operations and system checks; and 20 minutes miscellaneous for each EVA crewmember. (Note that we have assumed a zero prebreath time, which requires some combination of increased suit pressure, lower cabin pressure and/or higher R values.) Approximately half of this overhead activity must be carried out contiguously with the actual sortie, thus increasing the total EVA sortie work interval.

For optimization purposes, it is important to note that preparatory overhead time is essentially independent of EVA sortie duration. Consequently, if other factors are equal, greater productivity (i.e., the ratio of productive time to total time) is achieved by increasing the duration of each sortie, because the time penalty for preparatory overhead is thereby made proportionately smaller. Crew members recognize this instinctively, and they have consistently expressed a preference for fewer long-duration EVA sorties as opposed to an increased number of short-duration sorties (to attain equivalent total productive time). In fact, a telephone survey of five experienced EVA astronauts (Ross, Spring, McCandless, Musgrave, and

Peterson) revealed that they all agreed that EVA sorties of less than 4 or 5 actual "working hours" were probably too inefficient in terms of total manhour resources to meet station EVA support requirements, and they were unanimously opposed to a lunch break or rest period in the middle of a long EVA sortie and considered it a waste of time. Of course, the potential gain from increased sortie duration must be balanced against potential work capacity decreases, increased fatigue, incompatibility with IVA work schedules, etc.

"Coincident overhead" is our term for all the subsidiary tasks that an EVA crew member must perform, but that are not explicitly part of the assigned (productive) task sequence. For example, if the task is to remove and replace an ORU, the crew member may have to unstow tools and work aids (in addition to unstowing the replacement unit, which we would consider part of the productive effort), travel to the worksite (which might or might not be considered productive), set up restraint and positioning devices, tool/equipment caddies, lights, and other miscellaneous work aids. During the course of the work, he may have to pause occasionally to monitor suit systems or move lights to accommodate changing sun/shadow conditions, etc. All these actions fall within our "coincident overhead" category. Some of these items (e.g., lighting) are not unique to EVA (workers in one-g environments also sometimes need extra lighting, etc), but the ancillary devices associated with EVA are often complex and their use is laborious. In other words, the work aids and crew-assist devices that are essential in the EVA environment can themselves constitute cumbersome, fatiguing, time-consuming tasks. Because they are essential for many tasks, their cumulative effect can add significantly to the total EVA workload. In the following section we will discuss certain design features, taking into account the physiological work influences of the suit and the environment, which we believe will facilitate the use of these devices.

Obviously, an EVA crewmember's productivity is also greatly affected by the design of tools. We have already cited an example of the use of a power screwdriver to speed task accomplishment and eliminate the fatigue associated with multiple hand/wrist rotations. We also feel that tool design should consider two other factors: (1) the need to react forces and torques and (2) single-handed operation, that have not been emphasized in the development of the existing EVA tool set. However, tool design must be done on a case-by-case basis; and, except for general physiological considerations which will be presented in the following subsection, it is beyond the scope of this study.

This analysis completes our evaluation of generic EVA work influence factors. The final section addresses work optimization methods and design requirements in five topical areas.

2.4 EVA WORK OPTIMIZATION

The following five items summarize our EVA work optimization findings. Our rationale is as quantitative and objective as is possible with the current database. In those cases where qualitative results and opinion could not be avoided, we have tried to define methods for future quantitative analysis and suggest additional research to obtain the needed data.

2.4.1 Sortie Duration & Frequency

We believe it is unrealistic to propose an EVA schedule (i.e., sortie duration or frequency) that is not compatible with the duty cycle that NASA has apparently established as a standard for prolonged space flight (i.e., six 24-hour days per week divided into two 12-hour shifts per day). Consequently, we have accepted two ground rules: (1) the maximum duration of an EVA sortie should be such that the crew can accomplish the EVA and all related support activities within a 12 hour shift and (2) EVA sorties should be scheduled to coincide with the normal crew duty shifts. That is, we have not considered "swing shifts," "overtime," or other modified shifts for the EVA crew, because their physiological wellbeing might be adversely impacted, and their "floating" schedule might disrupt IVA schedules. Under these rules, an EVA could occur every day, or every other day, or every third day, etc within the 12-hour EVA crew shift.

The other major constraint on EVA scheduling is the Astronaut Office position, which requires at least one day of "rest" (i.e., normal IVA work load) between the days on which EVA is scheduled. As written, this constraint is independent of EVA sortie duration or total mission length. The Astronaut Office policy does not define a limit for sortie duration, but several crewmembers have stated that 6 hours of actual productive task time would be reasonable, and 8 hours an absolute maximum. (STS suit operations are limited to 6 hours actual working time by the capacity of the carbon dioxide scrubber.)

Of course, the most efficient use of total EVA manhour resources is achieved by maximizing the ratio of productive time to overhead time. This in turn dictates that

sortie duration be maximized, because overhead time per sortie is essentially constant (i.e., not a function of sortie duration), and hence longer sorties yield more productive time per overhead hour.

In view of these considerations, the optimum EVA schedule would consist of one maximum duration (e.g., about 7 working hours) sortie every other work day (i.e., 3 per week). This proposed schedule raises two kinds of concerns, however. First, can the crew sustain this level of physiological workload for mission durations of 90 days (or longer as the station matures)? Second, if the EVA resource provided by this schedule is not adequate to meet mission needs, can the work output be increased by schedule modifications? Inherent in the second question is a presumption that the Astronaut Office would accept longer or more frequent sorties if the attendant fatigue levels could be sufficiently reduced through the adaptation of more optimal task structuring or the development of improved restraints and tools.

Of course, one could simply add more EVA crew members. In fact, this is the proposed solution for EVA-intensive Shuttle flights associated with Space Station assembly. However, additional EVA crew members do not appear feasible on the permanently manned Space Station. If taken from the present crew complement of 8, they would unacceptably reduce manning for intravehicular activity (IVA), especially science; and if additional crew members were added, the impact to logistics and habitability accommodations would be severe.

Returning to the first question, our answer is a qualified "yes"; we believe the physiological effort to perform a 7 (or possibly 8) workhour EVA every other day is reasonable. Assuming that the workloads observed on EVAs to date are representative of future requirements, and assuming that the small sample of data from SKYLAB [20] is representative of human physiological adaptation to prolonged space flight; then it appears crews can perform 7-hour EVAs every other day without accumulative fatigue effects. Also, this schedule is compatible with proposed Space Station duty shifts and, incidentally, enables EVA crewmembers to be assigned to IVA to the maximum extent possible.

We realize that this rationale lacks quantitative justification, and hence is not a very satisfactory basis for EVA planning or equipment design. However, it is not as risky as it might appear for a couple of reasons. First it is anchored on flight

experience, albeit limited. Second, and perhaps most importantly, we believe that EVA physiological workloads can be substantially reduced through the introduction of improved equipment and modest task restructuring (Items 3, 4 and 5 below) thereby effecting a reduction of fatigue or alternatively an increase in productive output.

We turn now to the second question. Can the constraints be changed to allow a more intensive work schedule, if mission demands exceed the EVA work capacity provided by the proposed schedule? Our answer is that the potential for increased work output from changes solely in sortie duration or frequency is not very promising, primarily because one is simply "boxed in" by three facts: (1) EVA crewmembers must also perform substantial IVA roles, (2) there are very high overhead penalties associated with adding more sorties, and (3) increased sortie length not only drives crews toward exhaustion, but also encroaches on the 12-hour shift boundaries.

To illustrate the rather slim marginal gains in EVA productive manhours that might be achieved by schedule changes, consider the following rationale. There are basically two choices: increase sortie duration, or increase the number of sorties. The second option assumes one can decrease sortie duration sufficiently to reduce crew fatigue to the point that astronauts would be willing and able to perform additional sorties (i.e., more than 3 sorties per week).

The maximum feasible increase in sortie duration is about one hour (from 7 total hours to 8 total hours). Crews have already noted significant fatigue in EVAs of 6 or 7 hours duration, and they have stated that 8 hours is the maximum feasible. Furthermore, these perceptions are based on missions in which only one or two EVAs were scheduled. A prolonged mission with multiple EVAs can only make crew perceptions of fatigue worse, in our opinion. Note also that a sortie duration of 8 hours (from airlock depress to airlock repress) actually entails at least 10 total crew hours (i.e., 2 hours of overhead time), of which about 40 minutes is spent in donning/doffing equipment and real-time systems checks and hence is contiguous with the sortie. In view of the limited nutrition, hydration and hygiene provisions in the suit, 9 hours seems to be a reasonable upper limit for occupancy. Also, when essential crew habitability needs (meals, shower, etc.) are considered, the total crew time required to accomplish an 8-hour EVA plus overhead is very close to 12 hours. Therefore, the maximum gain in work output from increased sortie dura-

tion seems to be about 6 manhours per week (i.e., one hour per sortie which is equivalent to 2 manhours per sortie for 3 sorties per week.). Assuming that a 7-hour EVA actually yields 6 productive hours, the total EVA manhour resource as it is now defined is about 36 manhours per week, so the increase would amount to about 17% over the proposed schedule, assuming the added hour does not degrade work rate.

The other alternative is to increase the number of sorties to 4, or more, per week. The limit, of course, is 6 per week. To make this feasible one must reduce the fatigue which crews experience, otherwise they will not be able or willing to perform additional sorties. The only scheduling technique for reducing fatigue is to reduce sortie duration (other techniques for reducing fatigue are discussed in Items 3, 4 and 5 below). There is no quantitative method to determine how much reduction would be necessary. For discussion, assume that a 2 hour reduction in sortie duration would allow a sortie to be performed every day. The net gain would amount to 12 manhours per week. The gain in a 2-day period would be 4 manhours (the difference in one EVA of 6 productive hours versus 2 EVAs of 4 productive hours each, multiplied by 2 crewmembers) yielding a total gain of 12 manhours in a six day work week. This is a 34% increase in EVA manhours, but the penalties incurred tend to offset the gain and are probably prohibitive. Each additional sortie would add 4 manhours of preparatory overhead, or a total of 12 manhours per week, so that the cost of the additional EVA productive hours is very high, one for one in overhead time. Also the availability of EVA crews to participate in IVA would be reduced about 50% (from an estimated 48 manhours per week to about 24 manhours per week), and their efforts would be more piecemeal (i.e., short intervals preceding or following EVA every day.)

Neither scheduling alternative appears to offer enough improvement in EVA productivity to offset the potential penalties incurred. Consequently, if increased EVA output is required, we feel other answers must be found.

Before leaving the subject of scheduling we feel compelled to mention one other aspect of EVA crew physiological well-being, namely cardiovascular deconditioning. Crews are typically too fatigued after an EVA to perform conditioning exercises (e.g., the hour long period of exercise that is prescribed daily for station personnel). However EVA workloads, consisting of intermittent peaks and valleys in meta-

bolic rates and a high proportion of static loads, probably do not provide adequate cardiovascular exercise. It is not clear that exercising on "off days" (i.e., non-EVA days) is adequate for conditioning of these personnel over a 90-day period. Resolution of this question is clearly beyond the scope of this study, but we felt it necessary to identify the concern, because of its importance to crew health. We feel it is an issue that requires further study.

2.4.2 EVA Life Support System Requirements

The EVA life support system must satisfy the maximum metabolic demands an astronaut can generate in either of two scenarios:

- (1) A routine planned work interval of varying duration not exceeding 8 hours during which the average work rate will be limited to values that will not induce excessive fatigue.
- (2) A contingency scenario in which the astronaut is responding to a threat to life or mission, and thus the work rate may be the maximum that the crewmember can generate but the duration may be relatively short (on the order of one hour or less).

Obviously the second scenario is not a planned event and can occur anytime. In particular, it can occur at the end of a normal duration (e.g., 6 or 8 hours) sortie, and thus the system must have the capacity to handle the "worst case combination" of both scenarios.

The underlying physiological requirements which the system must provide in the first scenario can be determined in a relatively straight forward manner. First, if we select conservative values of metabolic rate from the basic data of Lehmann or Bink (i.e., we pick the higher of the two curves) for work durations of 1, 2, 4, 6 and 8 hours we obtain the following chart.

<u>Duration (hr)</u>	<u>1</u>	<u>2</u>	<u>4</u>	<u>6</u>	<u>8</u>
Metabolic Rate (kcal/min)	11	9.1	8.6	8.1	7.7
Cumulative					
Work Output (kcal)	660	1092	2064	2916	3696

Next we apply the population factor for which the conservative value is 1.6, and the Task Structure Factor which is 0.36 (as explained in Subsection 2.3.2 and 2.3.4), to obtain corrected values for EVA as shown below:

Duration (hr)	1	2	4	6	8
Metabolic Rate kcal/min	6.3	5.2	5.0	4.7	4.4

Cumulative

Work Output (kcal)	378	624	1200	1692	2112
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These values represent the work rate that an EVA astronaut could generate for various intervals of time without excessive fatigue.

To apply these values to the definitions of work capacity requirements for EVA life support equipment, they must be further manipulated to calculate the corresponding thermal loads, oxygen consumption and carbon dioxide removal rates. These quantities, in turn, are directly related to metabolic rates: the thermal load is approximately 80% of the metabolic rate; oxygen consumption in liters at Standard Temperature and Pressure is 0.207 liters/kcal of metabolic energy; and carbon dioxide generation is equal to oxygen consumption multiplied by the Respiratory Quotient which, conservatively, can be assumed to be 1.0 (It actually ranges between 0.7 and 1.0 for equilibrium metabolism, depending upon the relative composition of the food being consumed in terms of protein, fat or carbohydrate.). Using these factors we can determine values for the life support system specifications from the preceding chart, and if we combine the results, we obtain Fig. 2-11.

The data in this figure provides a basis for defining EVA life support system requirements for planned work intervals, but it does not include margins for excursions in work rate or extension of duration. (Nor for contingency scenarios which are discussed below.) Before addressing reserve margins, however, we feel it necessary to remind the reader of the qualitative and/or empirical basis of this data, and in particular about the uncertainties in the Population Factor and the Task Structure Factor. The Population Factor is based on raw measurements of the current (1987) astronaut population and has not been analyzed statistically nor demographically. The Task Structure Factor is even less scientific; it is, in truth, nothing more than an "averaged" ratio of observed EVA performance (based on a

EVA duration (hr)	1	2	4	6	8
Sustainable metabolic rate (kcal/min)	6.3	5.2	5.0	4.7	4.4
Heat generation rate (kcal/min)	5.0	4.2	4.0	3.8	3.5
O ₂ Consumption & CO ₂ generation rate $\left(\frac{\text{liters}}{\text{min}}\right)^{(1)}$	1.3	1.1	1.0	0.97	.91
Cumulative work output (kcal)	378	624	1200	1692	2112
Cumulative heat generated (kcal)	302	499	960	1354	1690
Cumulative O ₂ consumed & CO ₂ produced (liters) ⁽¹⁾	78	132	240	349	437
(1) Volumes at Standard Temperature and Pressure; Respiratory Quotient assumed equal to 1.0.					
R88-6169-031					

Fig. 2-11 EVA Metabolic Support Requirements for Planned Workloads Without Excursion Allowances.

sample of 11 two person sorties) to whole-body laboratory performance (measured during pseudo-tasks at essentially constant workload). Actual life support system specifications should not be established until one obtains statistically valid measurements of performance, which includes realistic EVA task structuring (excursions, etc). If such data cannot be obtained in a timely fashion, then life support systems specifications should include extra margins for uncertainty in the data base.

As we stated in Subsection 2.3, given the limitations of the current data base, it is almost entirely a matter of judgement to select appropriate levels of system reserves both for data uncertainty and for temporary excursions above the metabolic rates given in Fig. 2-11. We have used the athletic event data in Fig. 2-3 to gain some idea of the relative intensity of work rates that are possible with moderately conditioned individuals in excursions of various durations. Combining these values with a purely judgemental allowance for uncertainty, we recommend reserve factors of 1.7 for intervals of 1 hour or less, and 1.4 for intervals up to 4 hours. Beyond 4 hours, sustained excursions are very unlikely, but we feel that a factor of 1.2 is not unreasonable to account for basic uncertainties in the data. These "specifications" are shown in Fig. 2-12.

EVA duration (hr)	1	2	4	6	8
Reserve factor	1.7	1.4	1.4	1.2	1.2
Heat rate (kcal/min)	8.5	5.9	5.6	4.7	4.2
Total thermal load (kcal)	510	708	1344	1692	2016
O ₂ Consumption & CO ₂ removal rates ($\frac{\text{liters}}{\text{min}}$) ⁽¹⁾	2.2	1.5	1.4	1.2	1.1
Total O ₂ consumed & CO ₂ produced (liters) ⁽¹⁾	132	180	336	432	528
(1) Volumes measured at Standard Temperature and Pressure, Respiratory Quotient assumed equal to 1.0.					
R88-6169-032					

Fig. 2-12 EVA Life Support System Specifications

It should be noted that errors in these values would not create unsafe conditions, because the astronaut could voluntarily reduce his work rate if the metabolic demand exceeded the capacity of the life support system. Of course this "slow down" might degrade productivity, but should be acceptable if the workload was properly assessed and distributed during EVA timeline planning.

Total capacities required of the various subsystems for routine work loads can be set by simply considering the maximum duration case (with the uncertainty factor of 1.2), because we believe excursions cannot generate higher average metabolic loads. (They, like all burst/pause techniques, can only create higher intensity work rates for reduced time intervals.) Based on this rationale the total cooling capacity required to support 9 hours of EVA would simply be 9/8 of the 8-hour value, or 2268 kcals. Likewise the volumes of O₂ consumed and CO₂ that must be removed for 9 hours of operation would be 594 liters.

Note that these values pertain only to metabolic requirements; there are oxygen losses due to suit leakage and thermal cooling requirements associated with subsystem heat removal and radiation to/from the suit that must be accommodated; and they are not addressed here.

The final question to be addressed in defining the EVA life support system specifications is "What allowance should be made for contingency reserves?" Unfor-

Unfortunately there is essentially no quantitative data on this subject. We found no reports of tests to measure the maximum metabolic demands that a suited subject could generate in a simulated emergency. Also, there have been no cases in flight where an astronaut has been required to perform at maximum physiological capacity in a do or die situation. Probably, the situation that most nearly approximated an "all out" effort was the work of the Apollo 15 crews on the lunar surface, in which the metabolic rate of one crewmember was about 9.9 kcal/min (2350 BTU/hr) for an interval of perhaps 15 minutes [21, pp. 10-3]. A set of specification values based upon 9.9 kcal/min for a 15 minute interval was calculated using Equation 2.4 and a reserve factor of 1.7. The results are given in Fig. 2-13. As stated earlier, these demands could occur at any point in the EVA timeline, and the engineering design of the system should be based upon a worst case combination of these loads superimposed upon the routine workload requirements depicted in Fig. 2-12.

Before leaving this subject, we note that there is an intriguing possibility that improvements in suit design and/or task structuring might lead to increases in routine metabolic demands. We believe that fatigue from static loads prevents astronauts from achieving their true aerobic capacities. If these static loads were to be reduced by improved equipment designs or better task structuring, then dynamic

Time interval (min)	15	30	45	60
Maximum metabolic rate (kcal/min)	16.8	14.8	13.8	12.9
Cumulative workload (kcal)	253	444	621	775
Thermal rate (kcal/min)	13.4	11.9	11.1	10.4
Thermal load (kcal)	202	357	499	624
O ₂ Consumption & CO ₂ removal rate ($\frac{\text{liters}}{\text{min}}$) ⁽¹⁾	3.9	3.5	3.2	3.0
O ₂ & CO ₂ total quantities (liters) ⁽¹⁾	59	105	144	180
(1) Volumes measured at Standard Temperature and Pressure; Respiratory Quotient assumed equal to 1.0. Reserve Factor Equal 1.7 in All Cases.				
R88-6169-033				

Fig. 2-13 EVA Contingency Life Support System Requirements

work capacity might increase with a corresponding increase in metabolic demands on EVA systems. A conservative upper limit is probably 75% of the maximum whole body capacity for various time intervals.

We also note that the specifications given above are probably overly conservative and would result in excess system capacity. For example, the contingency cooling rate required for 15 minutes by our calculations is 7.9 kcal/min or 1880 BTU/hr. compared to a specified value of 1600 BTU/hr for a "15 minute peak thermal load" on the STS life support system. For a 9-hour total EVA duration we would require 594 liters of oxygen which is $(.0031 \text{ lbm/liter} \times 594 \text{ liters})$ 1.87 lbm. By comparison, the oxygen system quantity specification for the STS suit for a 6.5 hour interval is 1.22 lbm which is proportionately less. We do not wish to argue with the results of successful flight programs, but we feel that a margin of increased conservatism is justified because the present data base and physiological workload models do not give comprehensive, detailed insights into the ultimate metabolic load capacities of crewmembers. This is especially true if improvements in suits and ancillary equipment combined with more optimal task structuring, lead to increases in crew capability to achieve their true aerobic work capacity.

2.4.3 Physical Features of the Suit & Gloves

There is little question that the suit and gloves are the major factors which reduce both the static and dynamic work capacity of EVA astronauts. To deflect and hold the suit (or gloves) in any position other than the neutral position, requires static effort (force or torque) of such magnitude that it will induce fatigue in less than 10 minutes for an astronaut of average strength. When additional static effort is required by the external task, fatigue is accelerated. The time required to fully recover from severe static fatigue can be as much as 17 times the work interval. During typical EVA activities, astronauts probably do not achieve full recovery between tasks.

The suit also absorbs significant amounts of dynamic effort (work in the physics sense) in the forms of fabric work, slip ring work or flow work. When external tasks require repeated motions (scissors or ratcheting lever action devices for example), at least 15% of the total capacity of a typical crewmember is lost to suit work. (Paradoxically, when external force or torque is decreased by gearing or lever

ratios, the proportional amount of work that is lost to the suit increases, as will be illustrated in Subsection 2.4.5.1.)

We have identified some physical features of the suit which are correlated with these physiological effects, and the following discussion is intended to provide some insights which may be of benefit in the development and evaluation of new suit designs: Two categories of features are especially important to physiological work capacity.

2.4.3.1 Fit/Deformation - In Subsection 2.3.3 we gave an example of flow work effects which showed that the magnitude of this loss term is proportional to the amount of suit atmosphere which is forced from one part of the suit to another during deformations. This quantity can be reduced in two ways: First, improved fit will reduce the amount of atmosphere which resides in the "sheath" between the body parts and the suit inner surface in the neutral position. Second, reduction in the amount of volumetric change that occurs in various parts of the suit when they are flexed from their neutral position also reduces flow work. However, both of these "improvements" suffer from potentially offsetting drawbacks.

To achieve better fit in gloves, arms, etc, one may be forced to use more rigid construction materials and more extensive shape reinforcing techniques. The decrease in flow work might be offset by increases in the fabric work in such a design. Also, reduction of the thickness of the atmosphere sheath between the body and the suit may restrict airflow and degrade thermal conditioning.

One technique for reducing suit deformation is to use a hard suit with "constant volume" joints. (A "constant volume" joint as the name implies exhibits a constant internal volume regardless of the angle of the members forming the joint. The Ame's suit has this feature.) Such a design eliminates not only flow work but also the suit's tendency to align itself to a neutral position. This second result is especially beneficial because it eliminates a major source of static fatigue.

Again, however, there are negative aspects. In the design of the constant volume joint, rotating sections are substituted for fabric, with an attendant increase in the number of slip rings. Thus slip-ring work increases; and the forces which the

user must exert to rotate the rings is made even greater by the fact that the "torque axis" of the ring is not co-aligned with the normal axis of rotation of the wearer's body joint (elbow, hip, etc). Consequently there is a "secant" effect on the amount of torque that the wearer must generate. There may also be problems in the hard suit that are not physiological in nature. Additional rings mean additional rotating seals, which increases the potential for leakage. Such joints may also be more vulnerable to wear, damage, and accumulation of dirt or micro-debris in moving parts. They almost certainly require more servicing (and, possibly maintenance).

2.4.3.2 Pressure - For a given suit design, the energy required to rotate slip rings or deform the pressurized enclosure during movement is directly proportional to pressure. It is probable that the resistance to motion by the fabric is also an increasing function of pressure, though not necessarily in direct proportion. Furthermore, the tendency of the suit (at least the current, largely fabric suit) to maintain a neutral alignment (and hence the force or torque which the astronaut must exert to maintain a non neutral alignment) is also increased by increasing pressure. As a consequence, an increase in suit pressure increases both the dynamic and static workloads imposed on the wearer. Increased pressure may also "harden" the gloves and degrade dexterity and tactility. Therefore, the obvious recommendation from the viewpoint of work physiology seems to be to keep suit operating pressure as low as possible.

However, lower suit pressure implies increased prebreathing time which adds to an already burdensome level of overhead. In fact the expected demand for EVA manhours on the Space Station is so great that significant increases in overhead are simply not acceptable. Consequently, NASA is undertaking the development of a high-pressure suit. (An operating pressure of 8.3 psi is the goal, because this enables an astronaut to transition directly from a cabin at normal sea level atmospheric conditions to the suit without risk of bends, based upon an R value of 1.4.)

We recommend that NASA conduct a very careful trade study to weigh the gains from reduced prebreath requirements against the potential loss of work capacity, dexterity and tactility. Inherent in such a study is the utilization of quantitative techniques to objectively determine the effects of various alternative designs on physiological performance and fatigue.

2.4.3.3 Engineering Approach - Our purpose here is not to select engineering designs, but rather to point out the physiological work consequences of certain design features so that they will receive proper emphasis in future suit development and comparative testing. Furthermore, we wish to point out that there are relatively precise quantitative methods that could be made available to measure the work characteristics (forces and torques, flow work, etc) of alternative suit/glove designs. We strongly recommend that these methods be fully developed and implemented to supplant, or at least augment, the highly subjective (and sometimes quite inconsistent) testing methods that seem to be the industry standard at present.

2.4.4 Ancillary Work Aids

We will limit our observations on this topic to two generic improvements which we feel offer the greatest chance for significant reduction in fatigue during EVA (or alternatively increases in productivity).

2.4.4.1 Restraint and Positioning Devices - Current restraint and positioning devices, have three deficiencies. First, they are cumbersome to use. The fixed foot restraints, for example, require multiple rotations of a knurled knob to attach or remove the device at a worksite, and other knobs must be released to adjust the position and attitude of the platform and retightened to secure it. These rotational motions are precisely the kind of repeated movements which consume time (adding overhead) and induce fatigue. The safety latches on tethers, as a second example, often require two hands for operation because of their "safety lock" device (to preclude inadvertent release). If the astronaut literally has his hands full, he may have to interrupt the work sequence in order to hook or unhook the tether.

The second problem is that the existing devices do not provide adequate force/torque reaction. Obviously flexible tethers can react only tension loads; and, although some foot restraints will withstand 100 lbf in any direction, the astronaut often has no effective means of transferring the load from his hands/arms to his feet without incurring very high, unsupported torque loads on his waist, hips, knees, ankles, etc.

Lastly, the devices may unacceptably restrict a crew member's ability to make small changes in his position at a work site. The visibility and reach envelopes of

the suit in its neutral position are quite small. Thus, the crew member is often required to exert and hold relatively large forces and torques in order to flex the suit enough to see and reach objects that are required to complete a task at a "fixed" single work site. Such static loads lead rapidly to localized fatigue in the affected muscle groups.

One potential solution for these problems is the use of the RMS. However, the RMS can serve only one crew member at a time, and it requires essentially full-time support by an IV crewman. Furthermore, the force/torque reaction capabilities of the RMS are quite limited for certain combinations of reach and load direction.

Another possible solution is to simply install "permanent" restraint devices in copious numbers at all frequent worksites. This recommendation is made in the SKYLAB Lessons Learned document [20] for IV worksites. However, this approach is not practical for the large number of worksites and the relatively large reach/visibility envelope of many of the tasks that are expected on the Space Station.

We think a better solution is a modified positioning and restraint device that:

- Is easily deployed and adjusted using "single motion" one hand operation attachment devices
- Provides three point rigid support (such as the "telescoping pole" tethers that have been used by Grumman in neutral buoyancy work at MSFC to augment the foot restraints)
- Allows easy, one-hand operation to effect limited (a few feet probably) repositioning at a worksite to accommodate reach/visibility needs without relocating the restraint device.

2.4.4.2 Power Tool Use - One of the most fatiguing and inefficient uses of human work capacity in EVA is the performance of repetitive small motions associated with tools or devices that employ scissors, ratcheting levers, cranks, "screw driver" rotations, etc. In these activities, disproportionate fractions of the astronaut's energy are absorbed by the suit and excessive time is required. Power tools alleviate both these problems, speeding the task and reducing fatigue. There is one obvious limitation to this approach; the astronaut cannot be encumbered with a myriad of individual self-contained power tools, because the stowage and handling provisions would

be prohibitive. Therefore, we recommend the development of a tool system which would feature; (1) a single central power supply (possibly located adjacent to the portable life support system backpack), (2) appropriate power transmission devices (e.g., a flex cable drive or other device) attached to a "universal handle," and (3) a variety of "end effectors" which could plug into the handle and perform various functions (drill, saw, screwdriver, tube cutter, wrench, etc). We think this concept is feasible and offers considerable improvement in work capacity.

2.4.5 Task Structuring

As stated earlier, we believe that major elements of task scheduling, sequencing and procedures will be dictated by mission factors (day/night, expendables management, etc) or hardware design (the features of the item that is to be serviced or repaired). However, within those constraints, there are some techniques which could be employed to enhance EVA productive work capacity. They include the following:

2.4.5.1 Minimizing Suit Work - One intriguing outcome of our analysis is that in some cases, the structuring of a task to minimize strength requirements may actually increase the total metabolic effort that must be exerted. We will use a simple ratchet device to illustrate the problem. Assume that the task is to rotate a bolt a given number of turns (say N) against a fixed torque resistance (say T). To minimize the force that the astronaut must apply, one would make the ratchet handle (L) as long as possible or more practically, as long as necessary to reduce the required force to an acceptable value. (Note the phenomena which we are illustrating is the same if one used various gear ratios in lieu of changing the length of the ratchet handle, but the mathematics would be more involved. Thus for illustrative purposes we will use the simplest mechanical arrangement.)

Now, the mechanical work (W_M) to perform this task is independent of the ratchet, and is given by:

$$W_M = 2\pi NT \quad \text{Eq. 2.5}$$

Further suppose that the astronaut can move his hand a fixed distance (say D) back and forth to move the ratchet handle (i.e., his working reach is D), and that the suit work for each forward and back motion is W_D .

The total number (M) of back and forth ratcheting motions required is a function of the length (L) of the ratchet handle. To accomplish N rotations, the number of motions is:

$$M = \frac{2\pi LN}{D} \quad \text{Eq. 2.6}$$

and the total suit work (W_S) is:

$$W_S = MW_D = \frac{2\pi LN W_D}{D} \quad \text{Eq. 2.7}$$

The efficiency (E) in doing the task is the ratio of the mechanical work (W_M) to the total work, which is the sum of mechanical work (W_M) and suit work (W_S). Thus

$$\begin{aligned} E &= \frac{W_M}{W_M + W_S} = \frac{2\pi NT}{(2\pi NT) + \frac{2\pi LN W_D}{D}} \\ &= \frac{T}{T + \frac{(W_D)L}{D}} \quad \text{Eq. 2.8} \end{aligned}$$

Clearly, if the workload torque (T), the astronaut's arm movement (D), and the suit work for each movement (W_D), are fixed, then efficiency decreases as L increases, because increasing L in turn increases M, and more and more work is going into the suit.

Thus, we are led to the seemingly strange conclusion that to minimize total energy expenditure, for tasks which require repeated motions, the design should be such that the crewmember exerts the maximum possible strength on each stroke. (Of course, task design must consider the "weakest" crewmember in this situation.)

This example illustrates an insidious aspect of working in a pressure suit; namely, every movement in the suit is associated with an energy cost, even though little strength may be needed and little, or no, productive work may be accomplished. When tasks are planned, one goal should be to minimize the number and extent of repetitious astronaut movements.

2.4.5.2 Minimizing Static Workloads - The accrual of fatigue from static loads may be even more subtle. If the procedures for a given task require the crewmember to hold himself or a tool or piece of equipment in position against a resisting force of any kind (including the resistance of the suit to flexing), then static fatigue will occur very rapidly even when the required holding force is only 25% of the astronaut's strength. To the extent possible, task structuring should minimize "manual positioning" requirements, especially fine positioning or prolonged holding against an opposing force or torque.

2.4.5.3 Work/Rest Cycling - The application of work/rest techniques to "real world" tasks is problematic. Most tasks engender a natural sequence and timing of work, which cannot be expected to fortuitously coincide with ideal burst/pause ratios or intervals, especially since optimum interval lengths tend to be very short (on the order of 10 seconds) for high work burst intensities.

Consequently, we do not recommend any attempt to apply such techniques to EVA in a systematic manner. Instead, we recommend that EVA planners and astronauts be made aware of burst/pause effects so that they will recognize opportunities for their use which might arise fortuitously in the development of EVA task sequences and procedures or in "real time" execution. For example, tasks which require sustained steady application of force or torque might be altered to accommodate the substitution of intermittent exertions interspersed with pauses, with only minor changes to equipment or procedures. Long duration, high intensity excursions above the maximum sustainable work rate should be avoided, because they ultimately degrade the overall average work capacity. In short, a better understanding of work physiology on the part of EVA planners and astronauts might lead to more efficient task structuring, but mission and hardware factors must be given higher priority.

2.5 FINAL REMARKS

In closing, we note that gains in work capacity could undoubtedly be attained by training and by conditioning, especially of certain muscle groups which experience unusual demands in the EVA environment; and by screening the astronaut population to select personnel with greater strength and endurance, especially in their arms and hands. However, we have not pursued these ideas, because we feel the Astronaut Office would not accept formal physical conditioning or screening of the EVA cadre. In fact, our feeling is that equipment design and task structuring must proceed on the basis that physiological training, conditioning and screening of EVA candidates will not occur.

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3 - FOOD & WATER

This section is in response to Sections 2.2 and 2.4 in the SOW of the RFP, and was prepared by Dr. Malcolm Smith, Robert Santoro, and Dr. Paul A. Furr.

3.1 SUMMARY OF EVA METABOLIC ENERGY EXPENDITURE

Early investigators predicted that the energetic cost of life in the weightlessness of space would be much lower than for similar activities on Earth, since the astronaut would not have to work against normal gravitational forces [1,2,3]. This prediction turned out to be incorrect partly because it was based on Gemini missions, which involved little movement and metabolic energy expenditure. The significant biomedical findings from the Apollo program were [4]:

- Vestibular disturbances
- Less than optimal food consumption (1260 to 2903 kcal/d)
- Postflight dehydration and weight loss (recovery within one week)
- Decreased postflight orthostatic tolerance (tilt/LBNP tests)
- Reduced postflight exercise tolerance (first 3 days)
- Apollo 15 cardiac arrhythmias (frequent bigemini)
- Decreased red cell mass (2-10%) and plasma volume (4-9%).

The metabolic cost of EVA is dependent not only on the tasks performed, but also on the design of the pressure suit and life support system. Earlier Gemini pressure suits were stitched fabric suits that had a fixed resting position and minimum mobility for EVA. Considerable energy was expended working against the pressure suit. During Gemini 4 EVA, the heat removal capacity of the life support system was physically limited to about 225 kcal/h. The gas cooling life support system used on later Gemini suits had an increased physical capacity, but at acceptable body temperatures the system was limited to a heat removal rate of about 250 kcal/h. In the earlier Gemini EVAs, the use and evaluation of propulsive maneuvering units was emphasized. Beginning with Gemini 12 increased emphasis was placed on improved restraint systems. In summary, the results of the Gemini program indicated that EVA could be more difficult and physically taxing than had been

anticipated. More emphasis needed to be placed in crew training and in advancing the state-of-the-art in suit technology [5].

During Gemini EVAs, workloads in excess of 504 kcal/h were measured. These workloads were considered excessive and resulted not just from the tasks performed, but also from suit immobility, insufficient body-position aids, and thermal stress [6]. During these EVAs, metabolic rates were not measured directly. Instead, indirect measurements were obtained from electrocardiography and impedance pneumography. Unfortunately, heart and respiration rates measured this way are not as accurate as direct measures of metabolism (colorimetry). In addition, heart and respiration rates are affected by changes in psychological, physiological and pathological conditions that may, or may not, be related to metabolism [6]. From heart rates, metabolic rates were measured for Apollo and Shuttle crewmembers. For Shuttle EVAs, metabolic rates averaged 255 kcal/h and peaked at 389 kcal/h [7]. In contrast, the metabolic rate during EVA as measured from oxygen utilization averaged 196 kcal/h [6].

In addition to heart rate, energy expenditure during some of the Mercury, Gemini, Apollo, and Shuttle missions was determined from postflight analyses of the CO₂ absorbed [7]. With this technique, calculated metabolic rates for the first eight Shuttle IVA operations averaged 114 kcal/h for each crewmember. The average metabolic rates during Apollo, Skylab, and Shuttle zero-g EVAs are shown in Table 3-1 [7]. These rates were obtained from oxygen bottle pressure readings at the beginning and ending of the astronauts' EVA. Of significance is the decrease in the average metabolic rate from one space program to the next; a decrease due, in part, to improvements in space suit technology.

Problems with body cooling encountered during Gemini EVAs led to the development of a liquid-cooled garment (LCG) for the Apollo program. At work rates up to 400 kcal/h the LCG suppressed sweating, and at work rates as high as 500 kcal/h it permitted sustained EVA operations without thermal stress [7]. Over the entire Apollo program, the average metabolic rate for astronauts wearing LCGs was 234 kcal/h. With LCGs, metabolic rates could be calculated from differences between inlet and outlet coolant water temperatures as well as from differences in pre- and

post-EVA oxygen pressure in the Environmental Control & Life Support System (ECLSS). During Skylab EVAs, the metabolic rate averaged 230 kcal/h, ranging from 115 to 500 kcal/h [8].

Energy expenditure for tasks similar to those that will be performed in the Space Station era have been measured under simulated weightless conditions utilizing water immersion techniques (neutral buoyancy). Metabolic costs associated with the use of several restraint systems for maintenance work and for assembly of large modules were studied. Oxygen consumption was used as the measure of metabolic rate. During simulated weightlessness, the peak metabolic rate of 1052 kcal/h was measured during a jig assembly task [9]. This high rate was attributed to the test subject's lack of task experience and improper use of restraint systems. In contrast, during the large module assembly tasks, the subjects paced their work effort. As a result metabolic rates were lower (390 kcal/h).

3.2 NUTRIENT REQUIREMENTS

In over 200 citations reviewed, only a small percentage were directly related to EVA work, crew energy expenditure, food and water, and physical conditioning. In a recent publication on the research opportunities in nutrition and metabolism in space, Altman and Fisher [7] summarize and discuss dietary data related to both long- and short-term U.S. and U.S.S.R. space flights. Briefly, the points noted are:

- Diets for space flight have been based on the Recommended Dietary Allowances established by the National Research Council (1958) for people functioning in a one-g environment
- The evidence (at least from Apollo 7-17) suggests that either weightlessness or some other aspect of the space flight/mission environment causes crewmembers to restrict food intake below quantities available and necessary to maintain body weight
- On the basis of experience, and particularly with the advent of longer flights and extensive inflight exercise programs, total energy content of the diet in both U.S. and U.S.S.R. space programs has been progressively increased
- Dietary compensation for EVA crewmembers has not been addressed; yet, the caloric requirements of moderately active individuals might be increased by about 300 kcal/d over the needs of individuals engaged in light activity.

For very active persons the increase might be as great as 600-900 kcal/d. Just where the EVA crewmember would fall on this "scale" needs to be determined.

Altman and Fisher reviewed the recommendations of several scientific advisory groups and found them to be basically similar to those of the ad hoc Working Group from the Life Sciences Research Office, Federation of American Societies for Experimental Biology. This document contains an excellent review of space metabolic energy expenditure and nutrition research, with recommendations for additional food requirements research.

As noted earlier during Shuttle flights, EVA metabolic rates averaged 196 kcal/h for EVAs of 3.0-7.0 hours (Table 3-1) [7]. With Space Station EVAs of up to 8 hours duration and the potential for thousands of EVA hours per year, human efficiency and productivity are paramount to optimizing Space Station missions. Areas of concern to human proficiency and productivity include food and water requirements during EVA, effect of hydration on the incidence of decompression sickness, use of diet supplements and in-suit feeding versus taking a lunch break.

For reference, Table 3-2 contains the recommended daily allowance (RDA) (National Research Council, 1980) for the proportions of protein, fat and carbohydrate consumed by adult males in the U.S. whose energy requirements are approximately 2300-3100 kcal/d; athletes in training requiring more than 3000 kcal/d; U.S. astronauts from the Gemini, Apollo, Skylab and Shuttle missions; and U.S.S.R. cosmonauts on the Vostok, Voskhod, Soyuz and Salyut missions.

A survey of the literature relative to the physiology of man in space and EVA in particular, did not contain information specific to food and water requirements for EVA. The publications included in this section contain either EVA-specific data or appropriate baseline physiological findings indirectly related to EVA food and water requirements.

Table 3-1 Metabolic Expenditures During Extravehicular Activities

Apollo mission	Metabolic rate kcal/hr	Skylab mission	Metabolic rate kcal/hr	Shuttle mission	Metabolic rate kcal/hr
11	227 302 246 252	2	330 260 315 280	STS-6	146 206
12	221 252 202 234	3	265 240 310 250 225 180	41-B	191 239 166 186
14	229 252 277 247	4	230 250 155 205 145 220 220 185	41-C	204 246 235 194
15	252 204 260 204 219 255	Average	230	41-G	237 159
16	197 209 204 207 275 272			51-A	153 202 159 191
17	207 209 234 237 234			51-D	222 181
Average				51-I	200 192 211 202
				Average	196
Waligora and Horrigan, 1975		Waligora and Horrigan, 1977		Waligora, 1985	
R88-6169-013 (From: Altman & Fisher, 1986)					

Table 3-2 Proportions of Protein, Fat & Carbohydrates in U.S. Adults, Athletes, Astronauts & USSR Cosmonauts

	Protein	% Fat	Carbohydrate
U.S. adult males (2300-3100 kcal/d)	15	40	45
U.S. athletes (>3100 kcal/d)	15	30	55
U.S. astronauts	18.5	15.75	65.75
USSR cosmonauts	22.75	16.75	60.5
R88-6169-014		(From: Altman & Fisher, 1986)	

On four Gemini missions, EVAs lasted from 0.55 to 2.11 hours. Six Apollo lunar surface EVAs lasted from 2.43 to 7.62 hours each, with the average metabolic rate calculated at 234 kcal/h [10,11]. Skylab EVAs ranged from 0.61 to 6.90 hours in duration and for these EVAs, the average metabolic rate was 230 kcal/h. The Skylab EVAs were accomplished without any reported physiological difficulties.

During several Apollo, Skylab and Shuttle EVAs, crewmembers were provided with in-suit water and food, but the amount consumed was not reported. Systems for in-suit food and water were described by Huber et al. [12]. Water supplied but not necessarily consumed, varied from 125 ml (Apollo 14) to 490 ml (Apollo 15 & 17). In place of water, Apollo 16 crewmembers were provided with citrus-flavored beverage powders fortified with 10 mEq of potassium (as potassium gluconate). In-suit food was supplied in the form of "fruit bars" which were composed of natural fruits (apricot, cherry, plum, etc), gelatin, sugar and water. The energy value per fruit bar was approximately 188 kcal. EVA crewmembers on Skylab and Shuttle missions were provided with both in-suit fruit bars and water. However, these crewmembers chose not to consume the fruit bars during their EVAs. The degree of success or failure in using the fruit bars, or even the need for food and water during EVAs approaching 8 hours have not been reported.

EVA limitations due to food and water requirements would only be apparent if other limitations imposed by: (1) oxygen supply/carbon dioxide removal, (2) thermoregulation, (3) crew fatigue, (4) personal hygiene, and (5) crew comfort were negligible. These limitations alone or in concert would likely force a crewmember to abort an EVA long before food or water supplies became limiting. In the following paragraphs food and water requirements for the EVA crewmember are addressed.

3.2.1 Food

Investigations conducted in conjunction with inflight medical experiments during Skylab revealed that overall energy requirements inflight were not statistically different from those observed on the ground [13-16]. The roles of specific nutrients in maintaining homeostasis during other spaceflights have not been so clearly defined. Changes in body composition, decreased circulating red blood cell mass, loss of lean body mass, and cardiovascular deconditioning continue to elude complete definition [17-22].

In Skylab crewmembers some changes in body composition have been attributed to either an increased energy expenditure or a decreased metabolic efficiency leading to a catabolism of body fat [17,18]. Stereophotometric measurements pre- and postflight revealed significant volumetric losses in the abdomen, buttocks, and lower legs [23]. Skin fold thickness measurements also revealed volume losses over the triceps. However, these anthropometric and compositional changes were not always correlated with changes in body mass, and the cephalad shift of body fluids in the microgravity environment is, at least, partly responsible for the body mass changes noted.

Other Skylab studies revealed increased excretion of nitrogen and phosphorus inflight and indicated that there was an appreciable loss of muscle tissue among the flight crews [16]. This loss was probably due to disuse atrophy in skeletal muscles. Calcium loss has also been reported by several investigators [10,15,17,24], and correlated with X-ray changes noted in bone. Skeletal muscle deconditioning was predicted and detected in Apollo and Skylab crewmembers [14,16,20,25]. Muscle function in the arms and legs showed some impairment. Also, crewmembers temporarily lost some ability to perform programmed exercise tasks during the first 24 to 48 hours postflight. Finally, changes in electrolyte metabolism as a result of spaceflight have been described [14,16,19]. Postflight urinary sodium and potassium concentrations are reduced in spite of adequate dietary levels of these elements during flight [20].

3.2.2 Water

Water is the most essential "nutrient." Approximately 60% of body weight in the adult male is water, and 80% of circulating blood volume is water. Regulation of water balance in the body is carefully controlled. When the amount of body water lost is equivalent to 8-10% of body water, due to sweating, respiration or diarrhea, for example, physical performance is impaired even though mental performance may be unaffected. As more water is lost, physical and mental performance rapidly deteriorates. At approx 8% loss of total body water (about 6% loss of body weight - equivalent to about 4 liters) circulation becomes depressed, and renal failure develops with nitrogen retention (in the one-g environment). A man who has lost 5-10 liters of water is very ill, and death occurs when 20% to 25% of total body water is lost (10-15 liters). For comparison, the irreducible minimum water loss in the absence of sweating (urine, expired air, and insensible perspiration) is about

1200 ml/d, representing about 2.5% of the total body water in the average man [26]. Studies have shown that sweating rate is dependent on work rate [28-29]. Furthermore, sweating is apparently independent of skin temperature; even with cooled skin, sweating occurs during work. The stimulus to sweating is dependent on factors at the neuromuscular level as well as on an increased core temperature. If EVA work efficiency is to be maintained, water and solute lost due to sweating must be replaced so that proper osmolality and electrolyte balance can be maintained.

There is evidence from previous spaceflights that in adapting to microgravity, the body eliminates perceived excess fluids through a diuresis [15,30]. While the total effects of these findings have not been described, it is entirely possible that a crewmember may be slightly dehydrated prior to the start of an EVA.

Attempts to rehydrate the body prior to EVA must be taken with care. Small, frequent drinks of water are better than a single intake of the same quantity (e.g., 100 ml of water in one dose results in diuresis and greater loss of body water). This fact tends to favor the requirement for access to drinking water during the course of an EVA. Water requirements for EVA are like water requirements in general - they depend upon the rate of loss of water from the body. Healthy persons can readily lose 8 to 10 liters of water per day just through sweating alone.

3.2.3 Combined Effects of Food & Water

Studies reported by Dunn [31] and Dunn et al [32] used experimental animals to describe the suppressed erythropoiesis similar to that thought to occur in humans during spaceflight. Mice were subjected to a negative energy balance by reduced food intake and dehydrated by restricting water. Erythropoietic suppression was found to be primarily a result of reduced food intake with the severity augmented by dehydration.

Reduced food intake prior to EVA could result in increased loss of sodium, the main cation of the extracellular fluid. Compensation for the increased excretion of sodium is brought about by increased excretion of body water to maintain serum sodium levels (i.e., isotonic contraction of extracellular fluid). Excessive losses of sodium and water result in low blood volume, an increased hematocrit, lowered blood pressure, muscular cramps and vascular collapse.

In a 1961 report on the relative effect of water and carbohydrate supplements on work performance, six dogs were run to exhaustion on a treadmill [33]. When they ran after 17 hours of food and water deprivation, they were able to expend an average of 1190 kcal before collapse. With a carbohydrate supplement without water, they could expend 1300 kcal. When allowed to drink while running, they consumed an average of 1.5 liters of water and increased endurance to 2140 kcal. While not directly applicable to the EVA crewmember, studies of the effects of fasting and refeeding have demonstrated sodium and potassium diuresis during fasting in spite of adequate daily intake of water, sodium and potassium [34]. Refeeding with carbohydrates resulted in marked retention of sodium and reduction of urine volume. Urinary potassium losses were also reversed by the carbohydrate refeeding. Refeeding with fat aggravated a negative sodium balance. Refeeding with protein resulted in an initial rise then fall in sodium excretion. However, subjects equilibrated on a 2340 kcal diet followed by ingestion of a 600 kcal carbohydrate diet demonstrated natriuresis and kaliuresis. This study and similar studies underscore the premise that establishment of food and water requirements for the EVA crewmember requires careful integrated investigation of all environmental and physiological parameters and conditions under actual or high fidelity simulations of the EVA.

Improvements in protective systems (space suits) and basic life support systems for flight crews performing EVA have resulted in significant improvements in the value and work potential of man in space. These improvements have resulted in the desire to extend the duration and frequency of EVAs to the point where food, water, and the physical/mental ability of the crewmember become limiting factors of some significance. Review of published data and space flight anecdotal information reveals that food and water requirements have not been adequately investigated in the past.

The results of both space- and earth-based research indicates that the well-nourished and hydrated Space Station crewmember could accomplish EVA tasks at metabolic rates similar to those experienced in Apollo and Skylab (see Table 3-1). Furthermore, a water provision for crew consumption throughout the EVA is highly desirable and possibly mandatory for EVAs of more than 4 hours duration. The amount of water required would be based upon a determination of body water loss during the performance of specific EVA tasks.

Nutrient requirements necessary to maintain adequate metabolic levels in crewmembers in microgravity have been calculated and estimated by a variety of investigators. From the best current estimates, energy requirements in microgravity are similar to, or slightly greater than, those in a one-g environment; but, further studies are required before total energy needs can be reliably predicted for long term spaceflight operations. As indicated by lunar surface EVA data [7], healthy, well nourished crewmembers can accomplish EVA tasks at metabolic energy expenditure rates of 230-250 kcal/h without supplemental food for 8-hour periods.

Increasing the duration of EVA beyond 8 hours requires specific additional studies. Likewise, the frequency of space station EVAs has not yet been defined; though estimates have been made (see Subsection 1.4). Current requirements for Space Station impose a 48 hour recuperation period between EVAs in excess of 4 hours. This requirement appears to be adequate at least from a nutritional point of view. To establish models for predicting duration, frequency and total numbers of EVAs that could be performed without compromising crew health, investigations of EVA-specific physiology are required. In addition, food requirements before, during and after EVA should also be studied from a cost and health point of view.

3.2.4 Nutrient Requirements & Energy Expenditure

In trying to understand the relationship between nutrient requirements and energy expenditure, Altman and Fisher [7] have clearly summarized the problem from the research of others:

"Nutrient requirements can be altered by environmental stress, such as weightlessness, temperature extremes, and hyperactivity, thus creating dietary interactions that can alter the nutrient balance of the body as noted in the following examples (Olson, 1984). A high energy intake increases the need for thiamin which is required for a number of metabolic functions. High phosphate and calcium levels may exacerbate zinc deficiency, and high zinc intake may exacerbate existing copper deficiency. High protein levels from purified protein sources can increase calcium excretion, as well as increase the need for zinc and vitamin B₆. Nutrient absorption or bioavailability may be altered, also. For example, certain insoluble food components, some types of fiber and phytate in certain whole grain cereals and legumes, may decrease the availability of magnesium, calcium, and various trace elements in the gastrointestinal lumen. Still

another type of interaction is the suppression or inactivation of nutrients by environmental factors or ingestion of other foods, such as vitamin C inactivation by heat or oxidation, or the inactivation of biotin by the avidin in raw egg white (Dufour, 1984).

A nutritionally adequate diet can be related to the body's total energy expenditure as expressed in the activity of muscles, organs, systems, and mental/nervous processes. This need is regulated by thirst, appetite, digestion, and metabolism as well as by physical activity.

Weightlessness results in a substantial loss of the fluids and electrolytes that govern many of these functions (Leach, 1981), and the changes in physical work requirements may cause not only an altered energy output, but also a loss of protein nitrogen through muscle atrophy (Ushakov, 1980). The reduction in electromechanical stresses and other factors bring about a loss of calcium from bone. It has been suggested that metabolic and digestive processes undergo substantial changes, partly as a result of the altered stress environments and physical confinement (Popov, 1975).

Physical activity is the major variable affecting caloric expenditure and intake. Normally the responsiveness of the appetite mechanism is sufficiently precise to compensate for changes in daily physical activity, so that body weight and composition remain relatively constant. The caloric requirements of moderately active individuals might be increased by about 300 kcal over the needs of individuals engaged in light activity, but for very active persons the increase might be as great as 600-900 kcal/day (Buskirk and Mendez, 1980)."

3.3 EFFECT OF HYDRATION ON THE INCIDENCE OF DECOMPRESSION SICKNESS

The state of hydration of the EVA astronaut before and during EVA may be important when the astronaut is exposed to the hypobaric environment of the space suit. Adler [35], in a 1964 review entitled "Dysbarism," discussed the "electrolyte shift theory" in the etiology of decompression sickness (DCS), referencing studies done by Larkin and Watts [36], Warwick [37,38], and Ivy et al [39]:

Adler states:

"Larkin and Watts proposed a theory which ascribed bends to a shift of electrolytes in the body so that water was also shifted to the intercellular fluid. This, in effect, produced a syndrome similar to surgical shock and also similar to the mechanisms producing "miner's cramps" when ions are lost and water shifts into the tissues. Investigation of the actual blood chemistry was not performed in the subjects exposed to altitude. In an attempt to prevent a shift of electrolytes, subjects were exposed to 35,000 feet for 90 minutes with a standard exercise after a 7- to 10-day period in which calcium lactate, vitamins A and D, and 7.5 gm. of NaCl were given in addition to regular foods. According to the data, there was an increased resistance to bends in this group of tests as compared to the controls. They also reported that 2 subjects who usually drank large quantities of milk were the most resistant subjects to bends that they had ever seen. The studies by Warwick could be interpreted to support the electrolyte theory. By forcing fluids on 2 subjects who were highly susceptible to bends at 35,000 feet, one showed a marked increase in resistance to bends for 5 days while the second subject demonstrated a lesser degree of protection. When 2 subjects who were highly resistant to bends voluntarily restricted their fluid intake for 6 days there was a progressive increase in susceptibility to bends which disappeared when normal fluid intake was again permitted. On the basis of 17 subjects who made chamber ascents, on 14 consecutive days, to 35,000 feet for 3 hours, Warwick found that the incidence of symptoms was significantly higher in those who had low urine outputs as compared with those with high urine outputs."

"The above tests by Larkin and Watts were duplicated at 38,000 feet for 2 hours with a similar exercise on 7 individuals who had been repeatedly exposed to altitude. The incidence of bends was well known in these subjects since they had served as subjects on many types of experiments. The results of the tests with the salts and milk in these subjects showed no significant decrease in bends symptoms. If anything, the incidence was slightly increased."

Adler concludes with the following statement:

"In summary, it may be indicated that the crucial blood studies and dif-

ferentiation of various factors which are concerned with bends have not been studied adequately enough to completely void the idea that electrolyte changes do occur and contribute to some of the manifestations of altitude dysbarism. In this connection, collapse at altitude or after descent from altitude may be attended by a shock syndrome. Electrolyte alteration could be a factor in these instances."

In 1983, Waligora et al [40] showed that in five subjects, hydration with distilled water did not alter whole body tissue nitrogen washout characteristics associated with breathing 100% oxygen over a 3-hour period. Some older reports suggested that hydration with hypotonic fluids was beneficial in preventing Type I altitude decompression pain by augmenting tissue nitrogen washout [36-42].

In a 1986 update on DCS, Strauss and Samson [44] reviewed research [44-48] studying hydration states and stasis in the microcirculation. Others have found that DCS resolved in animals after administration of fluids such as Ringer's lactate, dextran, or blood [44]. There is a close correlation between the seriousness of the symptoms of DCS and the amount of hemoconcentration, hemostasis, intravascular bubbles and tissue ischemia [45]. In studies of the effects of decompression on platelet function and hemostasis, heparin and antilipemic agents provided protection from DCS [46]. During scuba diving, various degrees of dehydration have been measured along with post-dive increases in hematocrit, blood viscosity, platelet consumption, and hemoconcentration in asymptomatic divers even when decompression tables were followed as part of the dives [47]. During diving, increased vascular permeability contributed to hemoconcentration and stasis in the microcirculation presumably due to the inflammation and ischemia caused by intravascular bubbles [48]. In 1982, Bove [49] emphasized that when delayed, treatment for serious DCS cases was less effective because of the surface activity of the bubbles associated with DCS rather than because of the mechanical presence of the bubbles. In his view, the bubble becomes the nidus for clot formation, vascular permeability, and an inflammatory reaction at the interface of the vessel wall and the bubble. Once these bubble surface activity effects occur, restoration of blood flow (and thus oxygen delivery) in the microcirculation may be more important for recovery than reduction of bubble size. Hence, fluid administration is an important adjunct to hyperbaric oxygen treatment of DCS.

From the foregoing discussion, one must assume that any pre-existing state of dehydration, or dehydration occurring during an EVA evolution, can be expected to aggravate DCS; however, it is unclear whether or not dehydration will increase the incidence of DCS [50].

3.4 ELECTROLYTES

Spaceflight associated loss of electrolytes, has been noted by several authors [13,42,51,52] associated with bone demineralization, muscle and fluid loss. Though these changes are normal physiologic adaptations to weightlessness, they can compromise the astronaut's safety upon return to Earth and effect his performance/productivity while in space (in comparison to one-g standards). For example, Hawkins & Zieglschmid [52] reported significant inflight cardiac arrhythmias during the 12-day Apollo 15 mission, believed to be caused by a loss of potassium. With the additional physical workload expected to be placed on the EVA astronaut, an additional insult on the cardiovascular system secondary to electrolyte imbalances could most certainly, affect performance if not be outright dangerous to an astronaut isolated from the habitat. The effect on enzymatic reactions following the loss of such electrolytes as phosphorus, calcium, sodium, potassium and magnesium has not been fully explored [51,52].

3.4.1 Bone and Calcium

Of major concern is the effect of weightlessness on bone and calcium metabolism. Table 3-3 describes the changes in bone density and calcium balance observed as of 1982 [53]. Altman and Fisher [7] discuss these changes, of which there are several points of potential concern to the EVA crewman. One is the fact that in the 211-day Salyut flight in which crewmembers exercised approximately 3 hours per day, there was very little bone loss. If one accepts the thesis that the EVA crewmember will expend more energy over a given period of time because of EVA workloads being higher than IVA workloads, and longer exercise periods will ameliorate bone and calcium loss; then the total caloric and nutritional considerations may well be significantly different for the EVA crewmember. Whether or not the increased physical activity associated with EVA pressure suit work will serve as a substitute, in part, for planned exercise regimes needs to be determined. Altman and Fisher state, "If exercise is required to minimize demineralization, it will add another expenditure load relative to nutrition. More energy will be re-

Table 3-3 Bone & Calcium Changes Associated with Short-Term & Long-Term Space Flight

Physiological parameter	Short-term space flights (1-14 days)	Long-Term space flights (more than 2 weeks)	
		Pre- vs Inflight	Pre- vs Postflight
Musculoskeletal system & anthropometry			
Bone density	Os calcis density decreased postflight. Radius and ulna show variable changes, depending upon method used to measure density.		Os calcis density decreased postflight; amount of loss is correlated with mission duration. Little or no loss from non-weight bearing bones. RPB is gradual; recovery time is about the same as mission duration.
Calcium balance	Increasing negative calcium balance inflight.	Excretion of Ca in urine increases during 1st month inflight, then plateaus. Fecal Ca excretion declines until day 10, then increases continually throughout flight. Ca balance is positive preflight, becoming increasingly more negative throughout flight.	Urine Ca content drops below preflight baselines by day 10; fecal Ca content declines, but does not reach preflight baseline by day 20. Markedly negative Ca balance postflight, becoming much less negative by day 10. Ca balance still slightly negative on day 20. RPB: at least several weeks.
R88-6169-015		(From: Nicogarrian, 1982)	

quired, and some modification of the diet may be necessary in terms of vitamin D or calcium consumption, as well as other dietary components."

Calcium supplementation to increase calcium levels is controversial. Some scientists contend that much of the improved balance associated with increased calcium intake is an artifact of increased recovery [42]. That is, even if the supplemental calcium is absorbed, it is not necessarily utilized by bone. Furthermore, providing supplemental calcium in an attempt to replace calcium lost in association with tissue catabolism (especially bone) in the microgravity environment may be contraindicated as the hazard of kidney stone formation is increased in weightlessness secondary to high blood calcium levels.

3.5 LOSS OF CIRCULATING RED BLOOD CELL MASS

See also Subsection 4.3.2.

In both the U.S. program (Gemini, Apollo, Skylab, and Shuttle) and the Soviet flights (Soyuz-Salyut), one of the most consistent findings has been the reduction of plasma volume and circulating red blood cell mass (RCM) [54]. Erythrocyte and hemoglobin concentrations in the blood remained constant, suggesting that losses in the RCM are related to a complex series of physiological responses to weightlessness, the most significant of which may be plasma volume loss. Leon et al [55] observed that hemolysis of red blood cells in Wistar rats flown on Cosmos was related only to weightlessness and not to other conditions of space flight. This conclusion was based on the observation that little or no hemolysis occurred in those rats exposed to inflight centrifugations that produced an artificial gravitational field of one-g. Thus, in rats flown in space, increased hemolysis was considered to be the result of weightlessness alone. Note should be made of the fact that Soviet space flights have all been performed under normoxic conditions.

Johnson et al [56] and Kimzey [57] noted that plasma volume stabilized after the first few days of exposure to weightlessness, while RCM loss continued throughout in the Skylab 2, 3, and 4 missions (28, 59, and 84 days respectively). Dunn et al [58], in reanalyzing Skylab data, found a significant correlation between RCM loss and a decrease in caloric intake, changes in lean body mass, and exercise duration. They postulated that the loss of red blood cells may be an adaptation to body weight loss and could be prevented by techniques such as exercise to maintain lean body mass or increase tissue oxygen demands. Dietlein [59], in analyzing the results of Skylab states that RCM losses were apparently related to suppression of erythropoiesis rather than to increased red cell destruction. Vacek et al [60] support this thesis. They found that humeral and femoral bone marrow cells transplanted from rats flown in space produced fewer number of macroscopic colonies in recipients' spleens not exposed to weightlessness than did an identical amount of bone marrow from rats of control groups. In a review on this subject by Talbot and Fisher in 1985 [58], erythropoietic suppression was deemed due to alterations within the bone marrow as a consequence of weightlessness rather than a direct consequence of dehydration or change in the circulating levels of erythropoietin. Head-down tilt bed rest studies performed on healthy males by Dunn et al [61] also support the thesis that a decrease in RCM is not related to circulating levels of erythropoietin.

As noted in paragraph 4.3.2, Johnson [62] in a review of the subject postulated three plausible causes of bone marrow inhibition as the cause for decreased circulating red blood cell mass noted in weightlessness: (1) Inadequate caloric or protein intake, (2) Relative increase in the total body hematocrit as a result of the early inflight decrease in plasma volume, (3) A shift in the hemoglobin P_{50} as a result of an increased plasma phosphorus. Nutrition is implicated as a causal factor in the decreased RCM associated with spaceflight. Though the decrease in RCM may be physiologic, whether or not it will impact EVA work capacity has not been determined. Studies cited in paragraph 4.3.2 have shown that hyperoxia causes a decrease in RCM; and, this may be an additional factor impacting EVA work performance in higher pressure, single-gas space suits (8+ psia - a hyperoxic environment).

3.6 VITAMIN & MINERAL SUPPLEMENTATION

Table 3-2 shows the recommended daily allowance (RDA) (National Research Council, 1980) for the proportions of protein, fat and carbohydrate consumed by adults males and U.S. athletes in training compared with U.S. astronauts (Gemini, Apollo, Skylab and Shuttle missions) and U.S.S.R. cosmonauts (Vostok, Voskhod, Soyuz and Salyut missions). Vitamins and mineral supplementation in amounts over the RDA have been provided in some cases. For example, in the Apollo diet the RDA was exceeded for vitamins A, B₆, B₁₂, C, E and riboflavin, but was marginal for folic acid, nicotinate, pantothenate, and thiamin. The dietary components for the Shuttle OFTs as determined by Sauer and Rapp [63,64] were:

Total calories	3000 kcal
Protein	56 g
Carbohydrate	200 g
Vitamin A	5000 IU
Vitamin D	400 IU
Vitamin E	15 IU
Phosphorus	800 mg
Ascorbic acid	45 mg
Folacin	400 µg
Niacin	18 mg
Riboflavin	1.6 mg
Thiamin	1.4 mg
Vitamin B ₆	2.0 mg

Vitamin B ₁₂	3.0 µg
Calcium	800 mg
Iodine	130 µg
Iron	18 mg
Magnesium	350 mg
Zinc	15 mg
Potassium	70 mEq
Sodium	150 mEq

Altman and Fisher [7] in summarizing work done by Vorobyev et al 1983 and Yegorov, 1981, report the macronutrient and mineral content of the daily Salyut-6 diet. These diets contained vitamin supplements. The crewmembers were reported to have maintained a good health status and a "high work capacity" on this diet. The problem of nutrition and energy expenditure expressed by Altman and Fisher is, in fact, one of maintaining an Earth related physiological condition while the astronaut spends prolonged periods operating in weightlessness.

Other investigators [65-68] have studied the subject of nutrient requirements and energy expenditure in weightlessness. These investigations have included the use of food supplements such as amino acids, vitamins, minerals and nucleic acids relative to both physical and mental work capability. Though these research efforts may not have addressed the EVA crewmember directly, their findings support the conclusion that nutritional supplements may be important for optimizing EVA productivity. For example, Ushakov et al [65] performed experiments on seven male volunteers between the ages of 25 and 35 to determine the effect of amino acids, vitamins, minerals and nucleic acid supplements on a variety of mental and physical tasks. The results essentially show an improvement in both physical and mental tasks (Table 3-4, Fig. 3-1 and 3-2). Whether or not the same results would be obtainable in spacecrews who have undergone physiological adjustments to weightlessness can only be determined by repeating similar controlled studies in space.

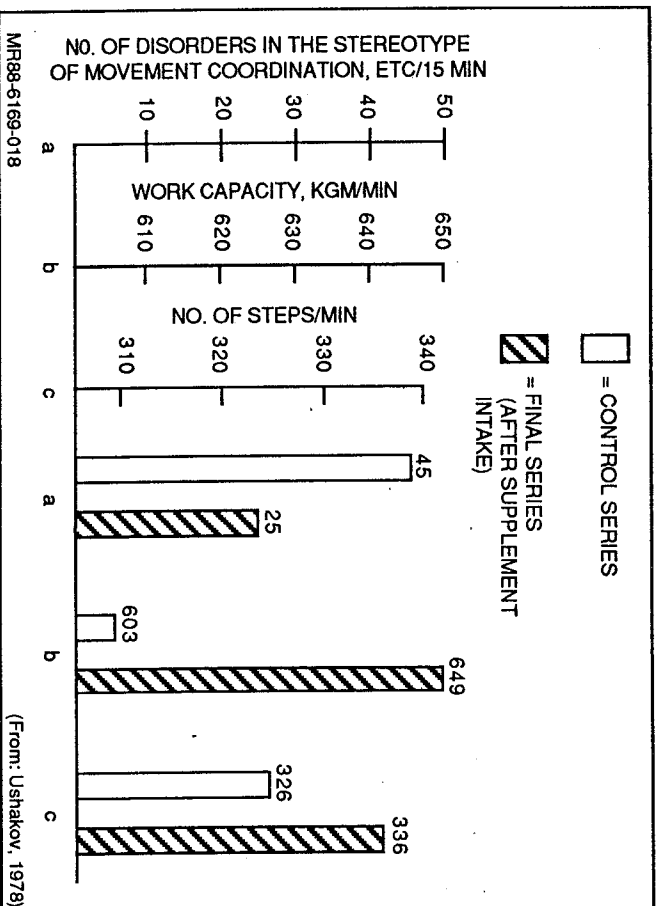
Goldberg and Chang [66] have indicated that leucine possesses unique regulatory and metabolic properties in muscle, including the promotion of protein synthesis and inhibition of protein degradation - something that may be of significant value

Table 3-4 Average Time Spent by the Test Subjects in Solving Arithmetic-Logic Problems

Experimental Series	Control Series					Final Series (After Supplement Intake)				
	Structural Elements of Work (Seconds)					Structural Elements of Work (Seconds)				
Experimental Conditions	Taking Decisions	Selecting Programs	Solving Problems	Checking Results		Taking Decisions	Selecting Programs	Solving Problems	Checking Results	
Before exercise	3.9	11.5	18.4	1.8		3.0	9.6	18.0	0.5	
After exercise	3.9	10.3	12.9	1.3		3.3	9.5	11.7	0.5	

R88-6169-017

(From: Ushakov, 1978)



MR88-6169-018

(From: Ushakov, 1978)

Fig. 3-1 Quantitative Parameters of Physical Work Capacity of Test Subjects

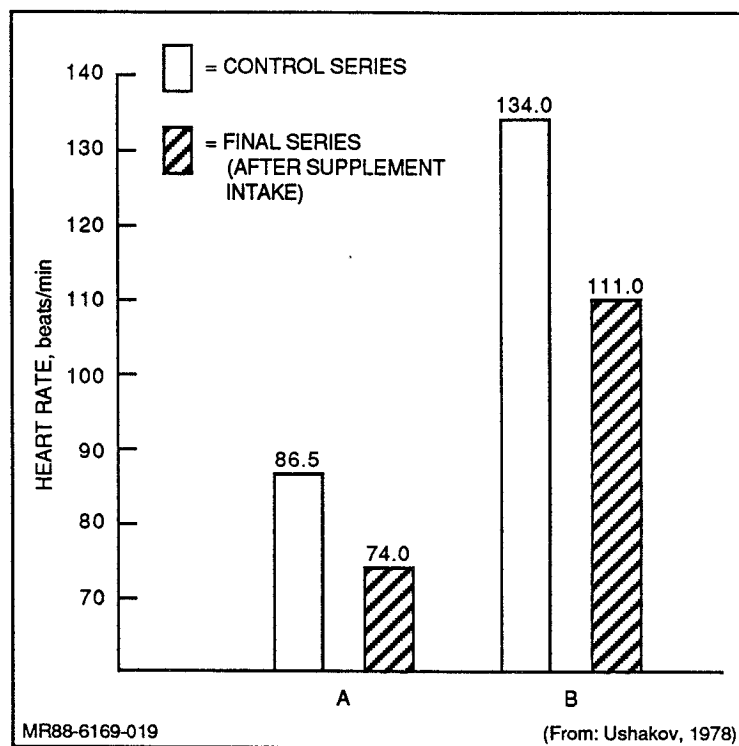


Fig. 3-2 Heart Rate of the Test Subjects Before (a) & After (b) Exercise

relative to the problem of muscle atrophy in spacecrews. Popov and Latskevich [67] have indicated that the cosmonauts preflight diet should be supplemented with methionine and aspartic acid; and that inflight and postflight diets should include not only the essential amino acids, but cysteine, arginine, proline and aspartic acid supplements.

3.7 IN-SUIT FEEDING vs LUNCH BREAKS

In the course of an eight-hour work period in a one-g Earth environment, a well nourished and hydrated worker with only a water provision should be able to work at an average rate of 200-250 kcal/h. To work at this level, one must be in good cardiovascular and musculoskeletal condition. However, in microgravity, a well planned exercise program to maintain good cardiovascular and musculoskeletal conditioning has yet to be proven. Therefore, whether or not an EVA astronaut can maintain an optimum level of work/productivity for up to eight hours without supplemental calories is questionable.

In addition to the physical aspects of EVA work, there are psychosociological issues to be considered in optimizing EVA productivity. For example, the "lunch break" is an institution in many cultures. Therefore, to design EVA missions that accomplish eight hours of productive (actual) work requires an analysis of work efficiency in relation to work/rest cycles (including time spent taking nourishment). In the following subsection, issues involved with in-suit feeding or taking a lunch break during the course of an eight-hour EVA are discussed.

Somewhat related to this problem is the problem of providing nourishment and water to military personnel forced to operate in a nuclear, biological and chemical (NBC) environment. The U.S. Air Force is developing an impervious protective garment (IMP) for up to eight hours protection from NBC hazards. Pending a solution to an existing thermal comfort problem, in-suit feeding will be implemented [LTC Raymond Gregory, USAF, AFSC, Wright-Patterson AFB; personal communication] incorporating technology developed at the U.S. Army Natick Research, Development and Engineering Center. The Army has successfully demonstrated the use of an in-suit feeding system for combat vehicle crews operating in a NBC environment. Individuals encapsulated for up to 72 hours subsisted on a prototype food and water system that permitted in-suit feeding through the protective face mask. This system was designed to operate in the one-g, zero-psig suit pressure Earth environment.

Other encapsulating, protective suits are employed by industry. For example, ILC Dover makes a system for use in a nuclear environment. In this system, an individual wears a throw-away suit for a short time - approximately one hour - while performing routine, scheduled maintenance. No provision is made for in-suit water or nourishment.

The logistics of packaging, suit servicing, etc is another area for evaluation. The potential advantages and disadvantages of locating liquid containers (water and liquid nutrients) external to the suit enclosure needs to be assessed. Servicing and reliability may be enhanced by installing these containers in the backpack, and incorporating quick disconnects for replenishment and manual override valves for controlling flow into the suit enclosure.

3.7.1 Advantages to In-Suit Feeding

3.7.1.1 Conservation of Time - Perhaps the biggest advantage to in-suit feeding is the minimization of time spent eating during a work period. With in-suit feeding, an EVA astronaut could literally eat while working. Therefore, the use of an in-suit feeding system can help optimize productivity by increasing the time available for productive EVA tasks. That is, in-suit feeding eliminates the time required to translate to and from the habitat, doff and don the pressure suit, prepare a meal and clean up after eating. However, in-suit feeding may or may not effect work efficiency (work accomplished per unit time).

3.7.1.2 Reduced Risk of Decompression Sickness - To reduce the risk of decompression sickness during EVA, the partial pressure of nitrogen in the tissues of the body will have been reduced at the time of the beginning of EVA unless EMU technology is at a point where the risk of DCS is virtually eliminated. Doffing the suit to take a lunch break may require that the habitat (airlock) be pressurized to a partial pressure of nitrogen that will not cause unsafe tissue renitrogenation when EVA resumes after eating. With in-suit feeding, the problems associated with an in-station lunch break are eliminated.

3.7.2 Disadvantages of In-Suit Feeding

3.7.2.1 EMU Contamination - With in-suit feeding, food particles could become loose within the suit and interfere with the personal life support system (PLSS). There is little information from past EVAs regarding suit contamination from the fruit bar nutrient system in that the fruit bars were not used.

3.7.2.2 Food Storage/Delivery Systems - To provide in-suit feeding requires a system to store and deliver nutrients to the astronaut. An obvious disadvantage of an in-suit feeding system is the cost of designing and developing a food storage and delivery system. In addition to cost, an in-suit feeding system would add to the complexity of the EMU with associated problems of reliability, maintainability and servicing. Some system complexity would be reduced if the EMU design permitted retracting the arms from the suit so that food and water could be grasped and moved to the mouth.

3.7.2.3 Summary - To successfully provide in-suit water and/or food for Space Station EVAs, the design of the system will be critical. The solution to the problem will depend, in part, upon the design characteristics of the EVA suit. If a crewmember has full use of his/her hands and arms inside the trunk of a suit such as in a "hard" suit, the design of an in-suit system for food/water delivery could be greatly simplified. Furthermore, in a hard suit, the crewmember could dock with the airlock to gain access to food and beverages stowed there. In the nominal or "soft" suit, food and water must be stowed in the suit prior to EVA, and the crewmember must access and deliver the food/water to his/her mouth using means other than the hands. The Gemini and Apollo pressure suits included a port in the helmet and a pontube through which food/water could be inserted and delivered to the crewmember's mouth. This system was tested and verified on the ground, but it was never employed in actual flight. In the Apollo program, extended EVAs occurred on the lunar surface. During these EVAs, crewmembers were provided with an in-suit bag containing water or beverage and food (fruit bar) attached to the helmet neck ring. The water or beverage was delivered to the crewmember's mouth through a tube with a valve which could be activated by grasping the tube in the mouth and bending it to open the valve. Water/beverage was then sucked from the bag.

3.7.3 Advantages to Taking a Lunch Break

3.7.3.1 Work/Rest Cycles - Taking a lunch break would provide a rest period that could be a factor in optimizing EVA productivity over the long run. Taking a break from an EVA task while remaining enclosed in the EMU may not be as restful as removing the helmet or exiting the suit altogether.

3.7.3.2 Waste Management - No U.S. astronaut has defecated during an EVA, some of which have lasted for up to 7.5 hours. However, during 8 hour Space Station EVAs, the amount of food required to support physical activity at potential metabolic rates of 200-250 kcal/h may lead to the need to defecate. Defecation during an in-station lunch break may be accomplished more easily and with less cleanup than defecating into a waste collection system in the suit. Urination occurs with greater frequency than defecation in most people; furthermore, in either space suits or in space stations, urination is more easily accomplished than defecation and requires less post-EVA cleanup. However, urinating during a lunch break/rest period

could lead to a smaller urine collection device requirement for the EMU. Finally, inadequacies in the suit waste collection system may necessitate an in-station break from EVA that is independent of the need for food and water.

3.7.3.3 Conventional Meals - Perhaps one of the biggest advantages to the lunch break concept is that conventional meals can be provided compared to the amount of food that can be provided via an in-suit system.

3.7.3.4 EMU Servicing - The time taken for a lunch-break could be used to service the PLSS - recharge/replace consumables. As a result, the size of the PLSS could be reduced.

3.7.4 Disadvantages of a Lunch Break

3.7.4.1 Conservation of Time and Consumables - The main problem with an in-station lunch break from EVA work is the associated increase in EVA overhead (non-productive) hours. Even without a lunch break, these hours are already undesirably high (Fig. 3-3). The translation between the work site and the airlock, the extra cycle of hatch operations, recompression and decompression, the "break" in suit integrity, and the extra suit checkout that must be accomplished will collectively increase the overhead by about 1 hour and 15 minutes. This added time might also extend the total duration of the EVA beyond acceptable physiological limits. Finally, the airlock operation incident to in-station lunch breaks. requires additional power for airlock evacuation and involves a loss of consumables.

3.7.4.2 Safety - When taking a lunch break, EMU wear and tear, and the potential for human procedural errors must be considered during the tasks incident to airlock operations and suit donning and doffing. The frequency and risks associated with these activities would increase if EVA operations included lunch breaks.

3.7.4.3 Summary - At this time, there is insufficient data to determine whether an eight-hour EVA with in-suit feeding is a more productive use of EVA time than a four-hour EVA with a lunch break. However, to resolve the in-suit feeding or lunch break alternatives, at least three factors should be considered: (1) appropriate nutrition, (2) proper exercise, (3) use of restraint systems. In comparing

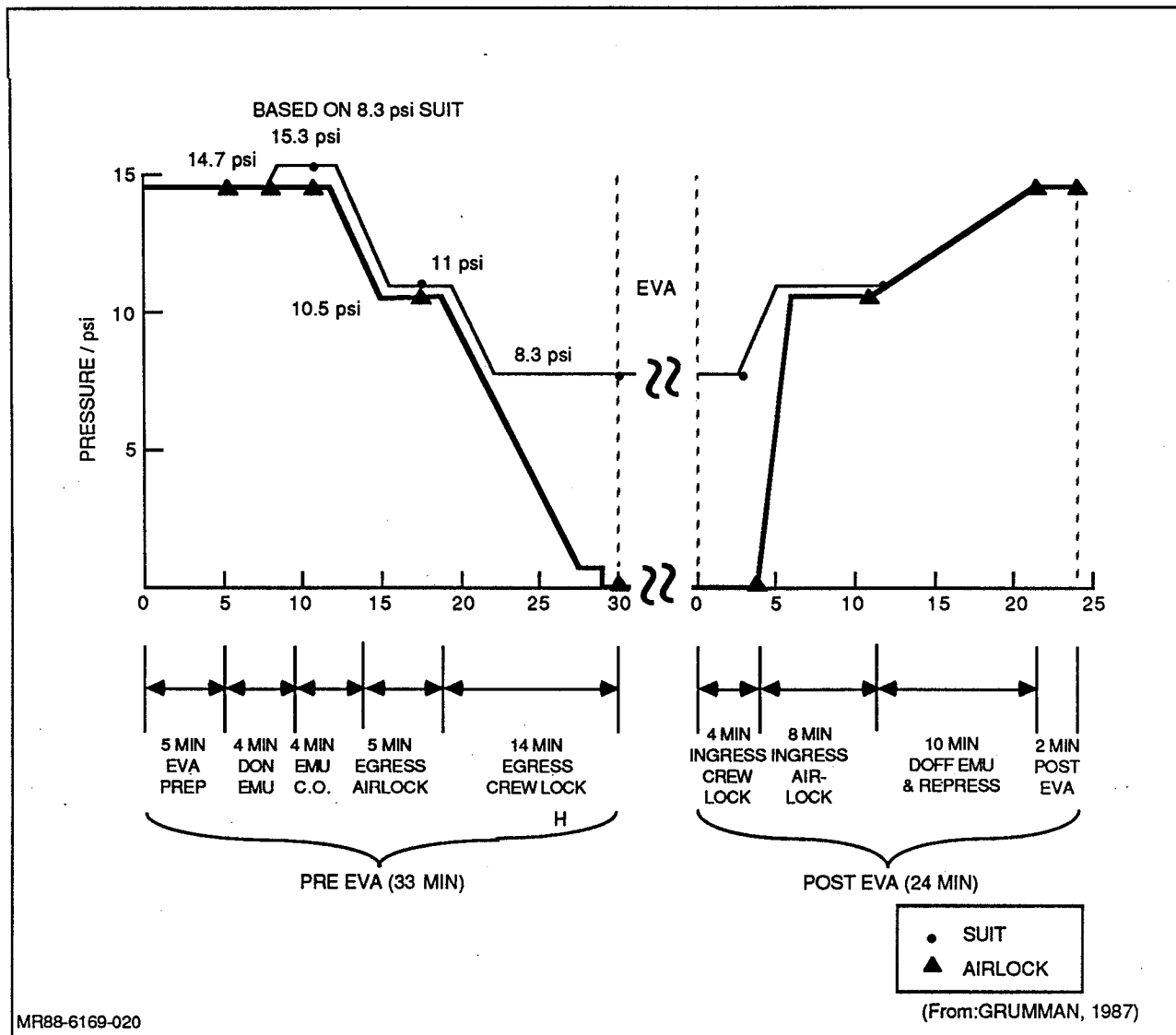


Fig. 3-3 Suit Pressure vs Airlock/Crewlock Pressure for EVA Cycle

uninterrupted, eight-hour EVA to an interrupted EVA with a lunch break, the proper design of restraint systems could minimize energy expenditure and consequently increase work efficiency. As previously indicated, another factor impacting EVA food requirements is the need to exercise to maintain physical conditioning. Also discussed previously, weightlessness effects the musculoskeletal system, causing a negative balance of phosphorus, calcium, magnesium, nitrogen and potassium accompanied by muscular atrophy. In Skylab 4 and the later Soviet flights, a bicycle ergometer and treadmill were used as exercise devices. With these devices, the negative mineral balances and muscular atrophy were minimized. The Soviets have also successfully used the penguin suit to minimize negative mineral

balances and muscular atrophy. Finally, increasing caloric intake and taking proper nutritional supplements should help reduce muscle atrophy and increase work capacity. However, additional studies are needed to define the proper exercise/nutrition combination to optimize a crewman's EVA performance.

3.8 CONCLUSIONS & RECOMMENDATIONS

- Unless studies show that taking a lunch break will substantially enhance overall EVA productivity, time, cost and safety considerations support a preference to in-suit feeding during an EVA
- There are alternative methods to the current in-suit fluid and food storage and dispensing systems. Trade studies should be undertaken to evaluate them. For example, a liquid nutrient system replacing the current "food stick" may offer several advantages such as tailoring to meet specific caloric, electrolyte, diet supplement and personal preferences (flavoring, sweetening, etc). The logistics of packaging, suit servicing, etc should also be reevaluated. The potential advantages and disadvantages of locating containers of water and liquid nutrients outside the EMU needs to be assessed. For example, servicing and reliability may be enhanced by installing these containers in the "backpack," and incorporating quick disconnects for replenishment. Manual override valves for controlling flow into the suit enclosure should be considered
- In addition to studies recommended by Altman and Fisher a comparison of bone and calcium metabolism between IVA and EVA crewmembers should be made during the early Space Station missions. The differences, if any, may be subtle and only meaningful if the studies are carried out in a long term microgravity environment
- There is sufficient evidence to implicate both weightlessness (as well as hyperoxia) as contributing to an anemia in space travelers. None of the literature reviewed gave any information as to the relative roles of each; and the presence of both stresses could be additive, synergistic or offsetting. Only the EVA astronaut will be exposed to both stresses; therefore, both the volume of circulating red blood cells and red blood cell indices should be compared for both the IVA and EVA crewman.

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4 - OXYGEN LEVELS

This section is in response to Section 2.1 in the SOW of the RFP, and was prepared by Dr. Paul A. Furr.

4.1 INTRODUCTION

4.1.1 Hypoxia

NASA is planning a normoxic environment of 14.7 psia with an 80% nitrogen/20% oxygen atmosphere for the Space Station; however, for some contingency operations a mild hypoxic environment may be unavoidable. Also, during long missions, physiological changes occur that may alter tolerance to hypoxia (and hyperoxia). Furthermore, if 10.2 psia is used as the barometric pressure for the Space Station as has been suggested, and the oxygen sensor is set at 26.5% (present Shuttle setting), the range of oxygen concentration may be anywhere from 23% to 30% (a mild hypoxia).

Providing a life support system that will prevent more than a mild hypoxic environment is the focus of this review. Considerations for the effect of mild hypoxia on EVA performance and the economy of the oxygen supply dictate the minimum concentration of oxygen required in the inspired gas mixture. Arguments for prevention of more severe hypoxia will not be addressed.

4.1.2 Hyperoxia

To perform EVA without the requirement of prebreathing for preventing decompression sickness, suit pressures higher than those presently used (4.3 psia) are required. Oxygen toxicity may be a concern if a single-gas system is used to maintain suit pressure as well as meeting breathing air requirements. If the risk of oxygen toxicity is adjudged to be unacceptable, the life support system and environmental control system manufacturers will be forced to develop a two-gas (O_2/N_2) system, with the inherent problems of reliability and higher costs associated with more complex systems.

4.2 MILD HYPOXIA

Hypoxia has been the subject of extensive research since the tragic ascent of the balloon Zenith in 1875, when acute altitude hypoxia claimed its first two victims, Croce and Sivel [1]. The results have led to today's requirement: (1) to use supplemental oxygen in U.S. military aviation at altitudes above 10,000 ft (a PAO_2 of 59 mm Hg) [2,3], (2) United Kingdom RAF regulations requiring aircrews use oxygen above 8,000 ft (a PAO_2 of 66 mm Hg) [4], (3) U.S. Federal Aviation Administration regulations (FAR) to require the use of supplemental oxygen by pilots in unpresurized aircraft when the time spent at 12,500 ft (a PAO_2 of 50 mm Hg) or above will exceed 30 minutes [5] (the same FAR requires that passengers be provided with supplemental oxygen at 15,000 ft - a PAO_2 of 43 mm Hg), and (4) U.S. commercial air carriers flying pressurized aircraft maintain a cabin pressure not to exceed 8,000 ft [6].

The above requirements are based on years of research. In 1964, Tune reviewed the 1950 to 1963 literature on the psychological effects of hypoxia [7]. He noted: (1) conflicting experimental evidence, (2) a disregard by investigators for contemporary developments, (3) the growing sophistication in psychology, (4) a lack of interdisciplinary research, and (5) that research into the psychological effects of hypoxia lagged behind studies of its physiological effects, and to an even greater extent, lagged behind psychology in general.

In 1978 and 1984, Ernsting reviewed studies of the effects of mild hypoxia on human performance [4,8]. He concluded that breathing air at altitudes up to 5,000 ft is acceptable for both crews and passengers of combat and passenger aircraft, and that during routine aircraft flights the maximum cabin altitude should not exceed 6,000 ft. The Soviets set the acceptable limit of hypoxia at 5,000 ft [9]. They indicate that "the partial pressure of oxygen must amount to 133 mm Hg as the optimum value"; however, for "short-duration flights a PO_2 of 104 mm Hg is acceptable" (11,500 ft). Ernsting's recommendation was based on the finding that a decrement in the learning phase of a complex task is just detectable at 5,000 ft, but is considerable at 8,000 ft [10]. Several studies have shown that breathing air at 8,000 ft produces a significant impairment of performance during the learning phase of a vigilance task [11,12], a complex psychomotor task [13] and a complex choice-reaction task [14]. In other investigations subjects performed two-dimensional tracking [15], mental problem solving and auditory vigilance tasks [16]. The

results confirm that the hypoxia associated with breathing air at altitudes up to 8,000 to 10,000 ft has no detectable effect on performance if the task was first learned at ground level.

Fowler et al (1985) reevaluated the minimum altitude at which hypoxic performance decrement could be detected [17]. Recognizing that vision plays a key role in complex psychomotor tasks, and that visual functions, especially night (scotopic) vision, are particularly sensitive to hypoxia (the effects being demonstrable as low as 4,000 to 5,000 ft [18,19]), they found little evidence that the mild visual decrements associated with hypoxia influence performance of complex psychomotor tasks. They referred to studies done by Tune who showed that the "generally accepted minimum altitude for detecting perceptual-motor effects has been 10,000 ft" [7]. Denison et al had earlier reported increased reaction times in subjects in a hypobaric chamber at 5,000 and 9,000 ft. The subjects performed a task involving spatial transformations (using a Mannikin test) while pedaling a bicycle ergometer at 27 W (23.2 kcal/h) to simulate aircraft pilot workload [20,21]. The increased reaction time was attributed to "task novelty," i.e., mild hypoxia affected performance while the task was first learned, but not after it had been practiced. The theoretical implication of this result was that learning, like vision, may be particularly sensitive to hypoxia. The idea that learning is sensitive to hypoxia influenced Ernsting to recommend that cabin altitudes be maintained at, or below, 8,000 ft [4].

On the other hand, Fowler et al (1985) stated that "other workers (Crow and Kelman 1971, 1973; Kelman and Crow, 1969; Kelman et al 1969) have been unable to detect a consistent performance decrement at 2438 m" (8,000 ft) [11,17,22,23,24]. They performed two experiments [17]. In the first, a spatial transformation task was performed at 27 W (see Denison et al above) while holding the arterial oxyhemoglobin saturation (SaO_2) at an altitude equivalent of 8,000 ft. No increase in initial reaction time occurred. In the second experiment, the SaO_2 was first stabilized to 8,000 ft equivalency, the 27 W workload was applied, and then the SaO_2 was allowed to vary freely while the spatial transformation task was performed. In this experiment, there was an increase in reaction time which was attributed to an accompanying decrease in SaO_2 . These results led them to conclude that the minimum altitude at which hypoxic performance decrements can be detected is greater than 8,000 ft. In addition, these results raised doubts about the validity of the "task novelty" hypothesis of Denison et al. The decrease SaO_2 in the second

experiment can be explained by a combination of hypoxia, exercise and hypoventilation due to breathing resistance. Fowler et al argued that this combination may have been a factor in the increased reaction time found by Denison et al who did not measure SaO_2 's [17].

More recently Fowler et al (1987) established 9,750 ft as a threshold for performance decrements due to hypoxia [25]. In establishing this threshold, they constructed a hypoxia dose-response function from measurements in six subjects who performed a Serial Choice Response Time (SCRT) task. This task gave a measurement of perceptual-motor performance under high and low lighting conditions (4.88 cd/m^2 and 50.0 cd/m^2) using LED displays. During task performance SaO_2 was decreased from 86% to 76% in steps of 2% (corresponding to PO_2 's of 8,900 to 11,400 ft. Response time was slowed in a dose dependent manner with a significant effect apparent at an SaO_2 of 82% (10,000 ft) but not at 84% (9,467 ft). By interpolation, the best estimate of the threshold to hypoxia was found to be 83%. This corresponds to an altitude of 9,750 ft - very close to the value proposed by Tune in 1964 [7], well above the upper estimate of 8,000 ft suggested by Denison et al [21] and well above the 6,000 ft level recommended by Ernsting [4,8].

In regard to the latter, the differences noted by Denison et al (1966) and Fowler et al (1985) are due, in part, to the differences in their experimental designs. Denison's et al estimate of 8,000 ft as the threshold for hypoxia is based on the use of a task involving spatial transformations (a Mannikin test) correlated with the determination of the atmospheric PO_2 . In contrast, Fowler et al based their estimate (9,750 ft) as the threshold of hypoxia on the SCRT task and the determination of the altitude corresponding to the SaO_2 . In summarizing these differences, Fowler et al [25] stated that Denison et al hypothesized that it was the novelty of the Mannikin test which made it particularly sensitive to hypoxia. It might therefore be argued that a somewhat lower threshold would have been found in their (Fowler et al, 1985) experiments if the SCRT had been novel, since the threshold for the Mannikin test has only been determined to lie between 8,000 and 12,000 ft. There are two problems with this argument according to Fowler et al. First, when Fowler et al (1985) eventually demonstrated an effect on the Mannikin test at 12,000 ft, it was not the kind predicted by the task novelty hypothesis. Second, other experiments have not indicated that learning and memory are particularly sensitive to hypoxia, and cites Crow and Kelman, 1973; Morgan and Green, 1983; and Paul,

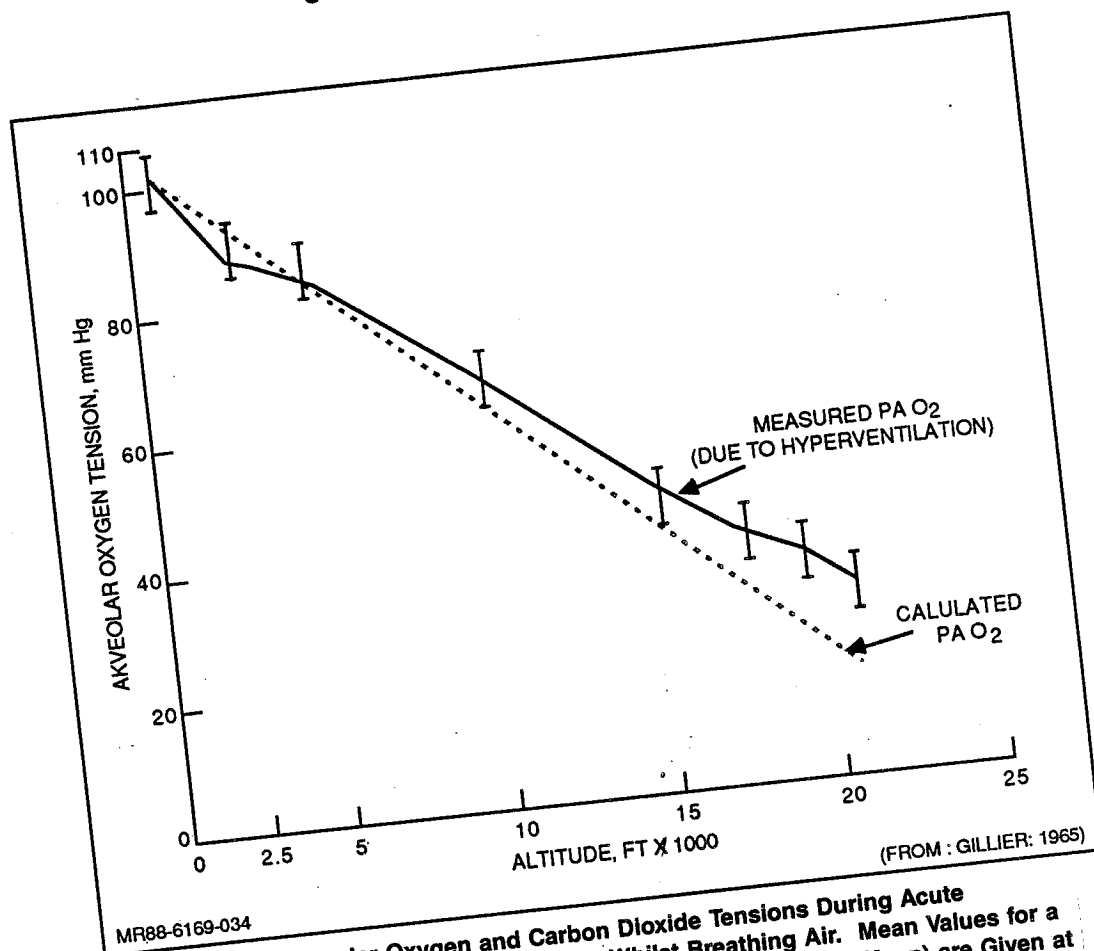
1983. Of course, the Mannikin Test might be more sensitive than the SCRT tests for reasons other than novelty, but this possibility is little more than speculation on current evidence according to Fowler et al [25]. They further stated that on the basis of the SCRT tests, it would be overly conservative to maintain cabin pressure at 8,000 ft as proposed by Ernsting.

4.2.1 Acclimatization to Hypoxia

With chronic exposure to low barometric pressures, altitude acclimatization occurs. The physiological processes which are involved include; (1) increased pulmonary minute volume and cardiac output, (2) increased diffusion capacity of the lungs, probably secondary to a rise in the pulmonary capillary blood volume, increased lung volume, and a rise in pulmonary arterial pressure, (3) a polycythemia secondary to hypoxic stimulation of erythropoietin release by the kidney, (4) an increase in tissue vascularity, (5) intracellular oxidative enzymatic changes, (6) a shift to the right of the oxyhemoglobin disassociation curve due to a decreased affinity of hemoglobin for oxygen resulting from an increase in red cell 2,3-diphosphoglyceric acid content, and (7) renal compensation for a respiratory alkalosis, through the excretion of bicarbonate ions [26]. These physiological changes are seen in the one-g environment at varying lag times following exposure to high altitudes. Figure 4-1, taken from Boothby (1944), shows that there is an insignificant change in lung ventilatory response associated with an acute exposure to an altitude of 6,000 ft (11.8 psia) while breathing air [27] - a scenario more in keeping with EVA except that the PAO_2 in the suit is more likely to be slightly hyperoxic in a single-gas system, negating any hypoxic stimulus associated with a low barometric pressure.

Haldane (1905) demonstrated that hypoxia is a much less effective stimulus of pulmonary ventilation than is an increase in alveolar carbon dioxide tension. No increase in pulmonary ventilation occurs with acute oxygen lack until the PAO_2 is reduced to about 65 mm Hg, and even a reduction to about 40 mm Hg will only increase ventilation by about one-third of its normal resting value. The pattern of pulmonary ventilation occurring in hypoxia does not represent a simple reaction to the reduction of PAO_2 , but is complicated by the fact that any increase in ventilation immediately reduces the $PACO_2$, which in turn, modifies the final character of the response. If the inspired $PACO_2$ is held constant by the addition of carbon dioxide, as might be the case if the suit carbon dioxide removal system malfunctions,

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Fig. 4-1 The Alveolar Oxygen and Carbon Dioxide Tensions During Acute Exposure to Simulated Altitudes Whilst Breathing Air. Mean Values for a Series of Subjects (With the Standard Deviation of the Mean) are Given at Each Altitude. The Broken Lines Depict the Alveolar Gas Tensions Which Would Result if no Ventilatory Response Occurred to Anoxia. (Boothby, 1944.)

the ventilatory response to hypoxia will be greater than when an increase in minute volume is allowed to reduce the $PACO_2$ (Fig. 4-2) [28].

With time, a slight increase in the volume of packed red blood cells occurs with chronic exposure to even moderate hypoxia as in altitudes of 4,000 to 6,000 ft. For males at sea level, the hematocrit is 47 (females - 42). At Salt Lake City, Utah elevation 4,200 ft, the hematocrit is 49.5 (females - 45) [29]. In space however the reduction in the circulating red blood cell mass is believed to be due to exposure to the normoxic, microgravity environment (weightlessness) [30].

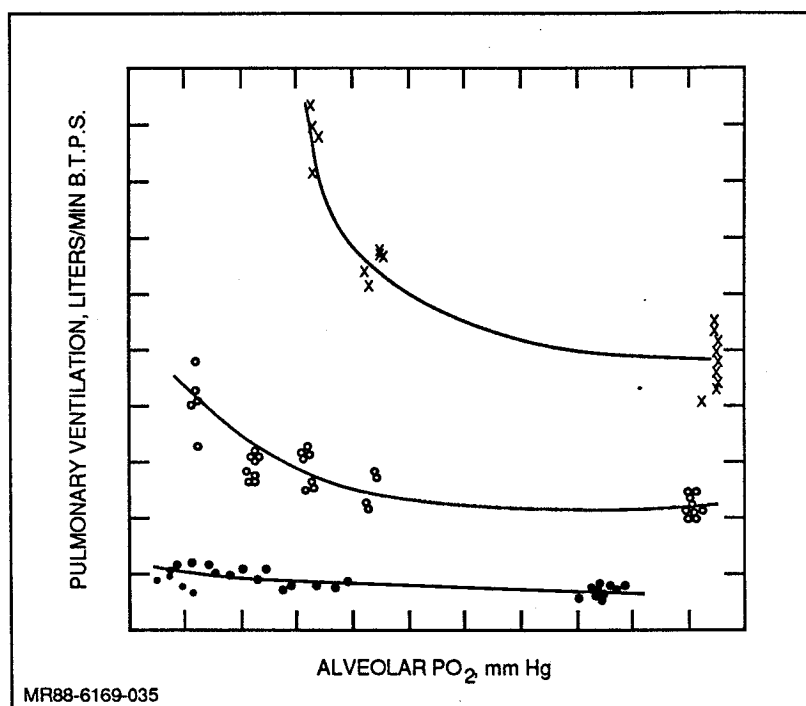


Fig. 4-2 The Relationship Between Alveolar Oxygen Tension & Pulmonary Ventilation in the Steady Physiological State at Alveolar Carbon Dioxide Tensions of 39.6 mm Hg (\bullet), 45.6 mm Hg (\circ), and 49.3 mm Hg (X). (Cormack et al, 1957.)

4.2.2 Pharmacological Intervention in Hypoxia

In 1985, Haywood et al reviewed the potential for pharmacologic enhancement of various physiological and metabolic processes relative to protection against acute hypoxic (altitude) hypoxia [9]. They found that considerable work had been done to seek ways to increase oxygen delivery to peripheral tissues and especially the central nervous system, primarily for alleviating clinical disorders (e.g., chronic pulmonary obstructive disease, respiratory distress in newborns, pulmonary hypertension, etc), but also to enhance respiration at altitude. The many components of the respiratory process provide several mechanisms whereby pharmaceuticals may increase oxygenation of the tissues during periods of reduced pulmonary function or decreases in atmospheric PO_2 . A decreased PaO_2 triggers a series of physiologic and metabolic events all "designed" to increase oxygen delivery to the tissues. The physiologic events shown in Fig. 4-3 represent a 25-second period of rapid ascent to very high altitudes. The cascade of respiratory events associated with rapid ascent affords the opportunity for pharmaceutical intervention at several functional and anatomical sites:

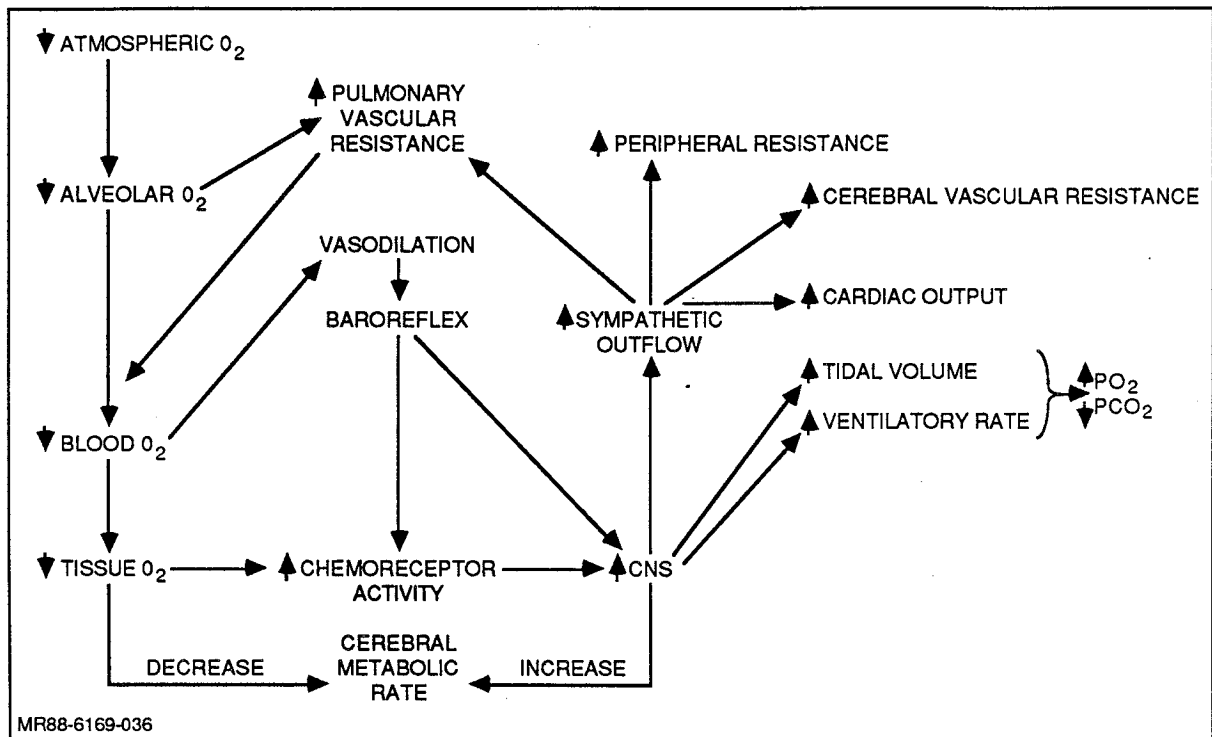


Fig. 4-3 Physiological Responses to Hypoxia

- Airway resistance
- Neural control of pulmonary function
- Oxygen transport
- Blood flow
- Cellular metabolism.

Although Haywood's et al treatise on the subject of pharmaceutical enhancement of respiratory processes is directed more towards the problem of acute hypoxic hypoxia (as seen in tactical jet aviation) than towards mild hypoxia, the potential for drug enhancement of the respiratory processes is more viable for milder forms of hypoxia. The drugs listed in Table 4-1 optimize the neural control of respiration, improve oxygen transport, blood-tissue exchange of oxygen, suppress metabolic rate, and enhance cerebral function. Haywood et al emphasized that "the major problems encountered with these antihypoxic agents center around side effects which may impair the mental or physical ability of pilots to perform their demanding tasks."

Table 4-1 Drugs Affecting Physiological & Metabolic Responses to Acute Hypoxia

Response to Hypoxia	Drug
Decrease airway resistance	Methylxanthines Terbutaline Atropine
Increased HbO ₂ dissociation	Acetazolamide H ⁺ PO ₄ Etidronate
Decreased O ₂ consumption	Beta blockers Etonidate Phenformin Y-9179 Benzodiazepines
Metabolic enhancement	Peracetam Naftidrofuryl Pyritinol Tinofedrine
Decreased pulmonary vascular resistance	Calcium antagonists Thromboxane synthetase inhibitors
Anaerobic metabolism	Phenformin
Increased cerebral blood flow	GABA CO ₂ Thromboxane synthetase inhibitors Adenosine
CNS control	Analeptics Naloxone Cholinergic agonists CO ₃
Increased chemoreceptor function	CO ₂ Naloxone Analeptics
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Certainly, further research is needed to identify ways of eliminating adverse side effects and examining the plausibility of the use of pharmaceuticals in mild hypoxic states that may be present in certain EVA contingencies.

Those studies which have focused on pharmaceutical enhancement of tissue oxygenation in hypoxic hypoxia states have concentrated on altitudes in the range of 14,000 to 30,000 ft. Haywood et al concluded that perhaps the most promising pharmacological approach to enhancing tissue oxygenation and prolonging performance involves the use of a new class of drugs referred to as nootropic agents. Also called "metabolic enhancers," these pharmaceuticals increase the resistance of the brain to stress. Although the mechanism of action is not known, tolerance to hypoxia is improved and learning is enhanced.

4.3 HYPEROXIA

An estimate of the probability of oxygen toxicity associated with a single-gas space suit system will primarily be concerned with: (1) changes in pulmonary function, as measured by a decrease in lung vital capacity (VC), which is the primary quantitative index of the severity of pulmonary oxygen poisoning, and (2) changes in the circulating red blood cell mass (RCM) [30,31,32]. The highest PO_2 that can reasonably be anticipated in a space suit is somewhat less than 14.7 psia - the present planned Space Station barometric pressure. However, a more reasonable suit pressure with a single-gas system would be between 8.5 and 9.5 psia. Krutz et al exposed 53 male subjects to simulated EVA workloads and found no decompression sickness (DCS) symptoms, nor severe bubbling above a decompression to 9.0 psia [33].

4.3.1 Pulmonary Function

Several excellent review articles have been published in recent years on the subject of oxygen toxicity. Each describes the pathogenesis of oxygen toxicity with emphasis on physiological changes (considered to be readily reversible) and pathological changes (which are more permanent). Roth reviewed the physiological problems of humans exposed to oxygen tensions from 0.2 to 1.0 ATA, with emphasis on the criteria for establishing a space cabin atmosphere for several weeks of continuous occupation [34]. Clark and Lambertsen reviewed 75 experiments in which animals were exposed continuously to an oxygen tension of 0.9 to 1.0 ATA for 39 hours to over 68 days (survival times) [31]. Other research efforts reviewed by

Clark and Lambertsen, involved continuous oxygen exposures from 1 ATA to as high as 6 ATA for 2 to 72 hours. Signs and symptoms of oxygen toxicity noted most frequently in the research reviewed by these authors involved progressive deterioration of the lungs in two overlapping phases. The first is an acute exudative phase consisting of interstitial and alveolar edema, intra-alveolar hemorrhage, fibrinous exudate, hyaline membranes, swelling and destruction of capillary endothelial cells and destruction of Type I alveolar epithelial cells. The second consists of a subacute proliferative phase characterized by interstitial fibrosis, fibroblastic proliferation, hyperplasia of Type II alveolar epithelial cells, and at least a partial resolution of earlier exudative changes. Swelling and destruction of pulmonary capillary endothelial cells, along with interstitial and perivascular edema, are the first toxic effects detectable during the development of pulmonary oxygen poisoning. These changes can be readily measured as a decrease in lung VC.

Lambertsen has summarized the sequence of acute physiologic effects of oxygen in man (Fig. 4-4)[35]. Each of the effects has been demonstrated at a pressure of 1 ATA and, except for chemoreflex suppression, at 3.0 to 3.5 ATA. Each should be considered spontaneously reversible and a physiologic rather than a toxic effect. When oxygen is administered at high partial pressure, the initial effects - change in PaO_2 and SaO_2 - lead to readjustments in a series of related physiologic functions. Direct and indirect effects of these readjustments emerge, often with the indirect effects predominant. In a normal individual at rest, the magnitude of the changes in physiological functions are proportional to the oxygen level. As the five sets of opposing arrows in Fig. 4-4 show, breathing oxygen at high pressures results in conflicting physiological effects that can lead to a new state of dynamic balance. In an abnormal state, the severity and even the direction of changes produced by high oxygen pressures depend on the balance of physiologic and pathologic factors prior to the beginning of oxygen breathing.

Clark and Lambertsen have generated a family of hyperbolic pulmonary oxygen tolerance curves (Fig. 4-5)[31,35]. These curves show the duration of continuous oxygen exposure at various partial pressures that will induce different decreases in VC in 50% of individuals. The tolerance curves in Fig. 4-5 assume that: (1) at an infinitely high inspired PO_2 , the duration of pulmonary or central nervous system (CNS) oxygen tolerance will be nearly zero, and (2) at some sufficiently low inspired PO_2 there will be no detectable limit to oxygen tolerance. At approximately 0.6 to

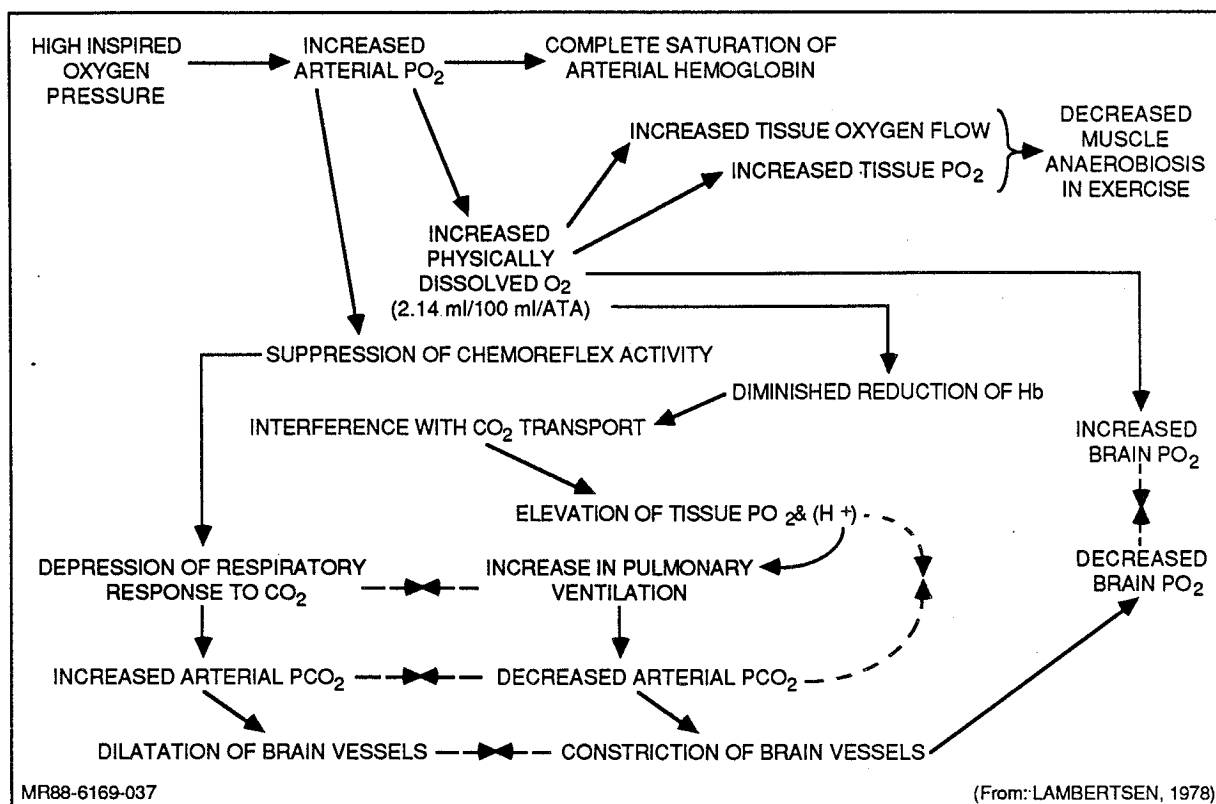


Fig. 4-4 Sequence of Acute Physiologic Effects of Oxygen in Normal Men

0.7 ATA PO_2 , the less than 2% delta VC curve becomes asymptotic at 30 hours of continuous oxygen breathing. The PO_2 that will produce borderline pulmonary toxicity is considered to be 0.5 ATA since 0.5 ATA does not cause a problem in 14 days of continuous exposure to 100% oxygen [36,37]. The CNS oxygen tolerance curve represents pressure/duration exposures generating a 10% incidence of some form of CNS effects, including, but not limited to, convulsions. The curves in Fig. 4-6 show the variation in susceptibility to a uniform degree of pulmonary oxygen poisoning represented by a 4% decrease in VC [38]. After 30 hours of breathing oxygen at a PO_2 of approximately 0.6 to 0.7 ATA, the susceptibility is only about 10%.

In a 1960 review of oxygen toxicity research, Michel found "that although many investigators have concluded that oxygen can be inhaled in concentrations up to 60% at 760 mm Hg pressure (8.83 psi PO_2) for infinite periods of time, these conclusions are based on the results of either animal or human studies of rather short duration"

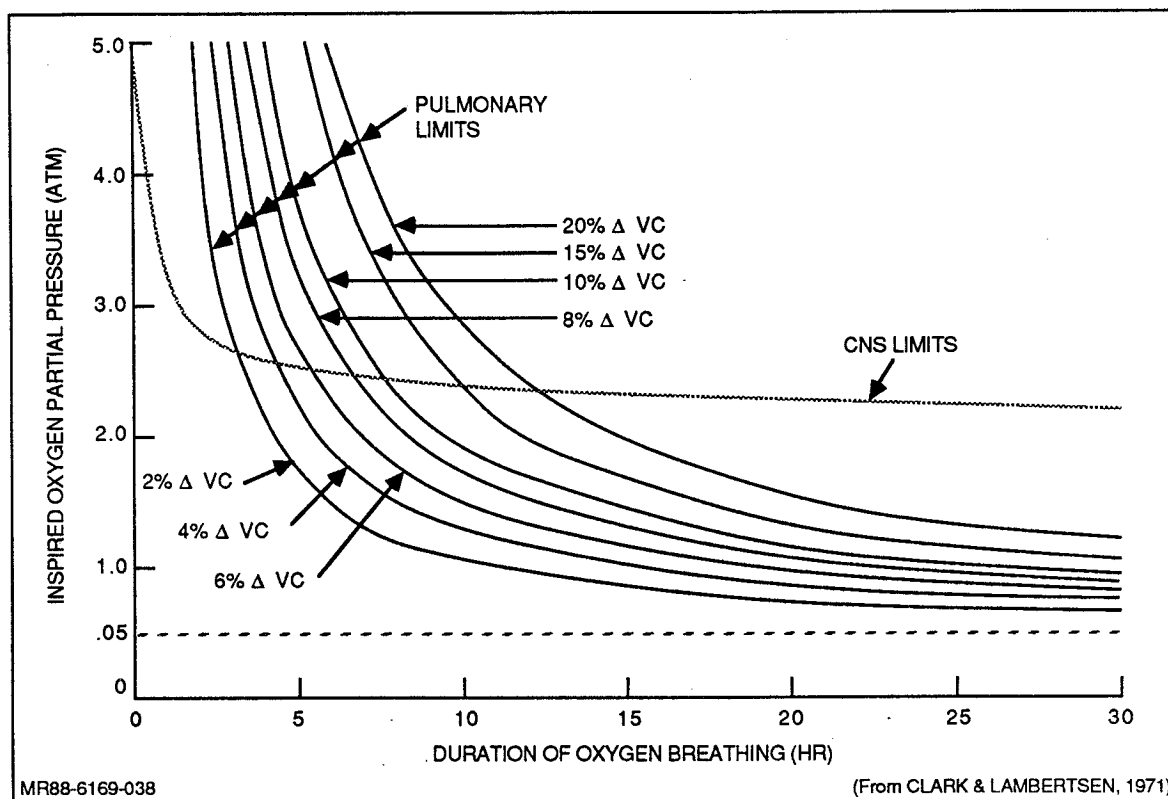


Fig. 4-5 Pulmonary Oxygen Tolerance Curves in Normal Men (Based on Vital Capacity Changes in 50% of the Subjects)

[39]. An example of one such study was conducted by Ohlsson in 1947 [40]. He exposed six healthy males to a PO_2 ranging from 11.46 to 12.9 psia for 53 to 57 continuous hours. Four of the six subjects experienced substernal distress while five showed a decrease in VC. The experiments were carried out in a chamber at 1 ATA with 1% carbon dioxide. In four of the six subjects, carbon dioxide was allowed to gradually increase to 2.7% toward the end of the experiment. During this time, there were no changes in hematological parameters that could be attributed to hyperoxemia. There were no significant lasting physiological effects of the hyperoxemia. Michel also found that among six male subjects continuously exposed to a PO_2 of 418 mm Hg (8.1 psia) for seven days, there were no significant effects on general appearance, activity and physical well-being. During the hyperoxic exposure, "pulmonary irritation" occurred (substernal "tightness" on deep inspiration), two subjects had a decrease in VC, and there was an occurrence of an area of probable atelectasis on X-ray examination in one subject (one of the two subjects with a decreased VC). However, no symptoms or signs of atelectasis remained after 24 hours.

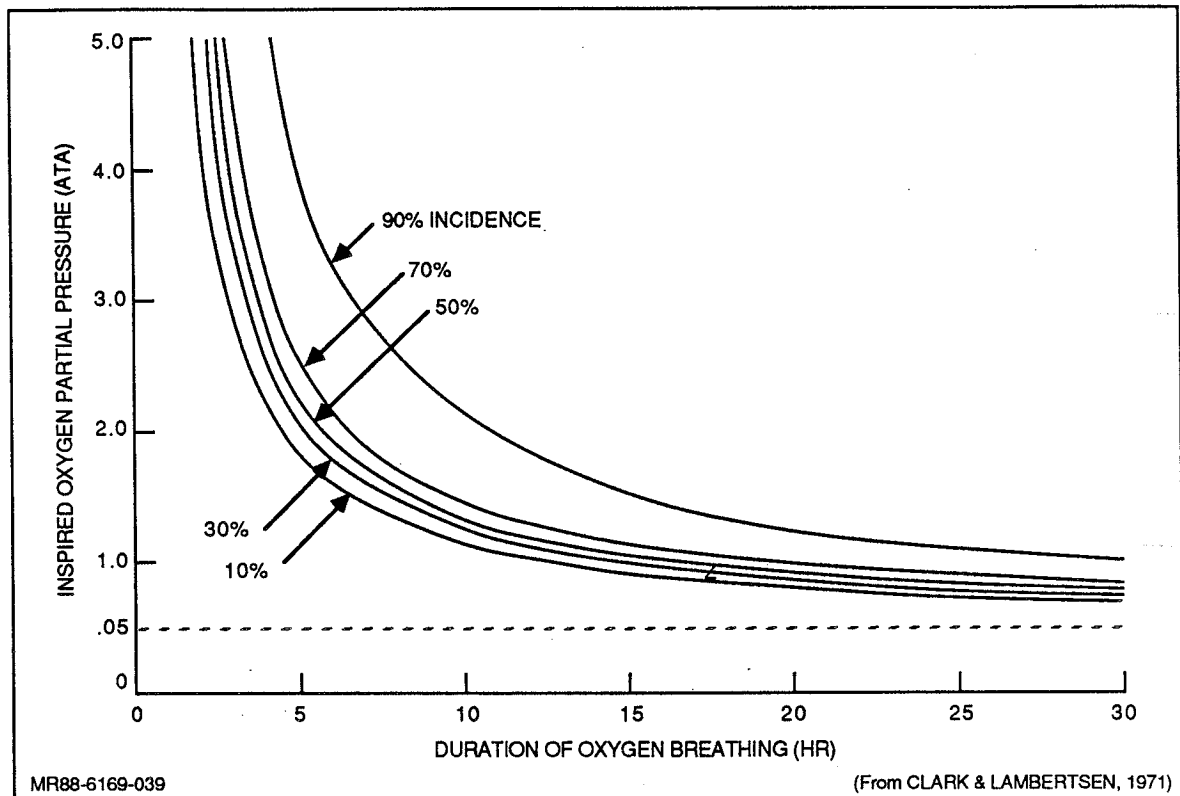


Fig. 4-6 Pulmonary Oxygen Poisoning Susceptibility for Normal Men (Based on a 4% Decrease in Vital Capacity)

Cellular enzymatic activity is both dependent on oxygen and poisoned by it. As exposure to hyperoxygenation (> 0.2 ATA PO_2) begins, the development of oxygen toxicity also begins and proceeds along different time courses in different organs. It is likely (though essentially unstudied), that recovery also occurs at different rates not only for different organs, but for different enzymes within a single cell [36]. A useful approach to extending oxygen tolerance is periodic interruption of the hyperoxic exposure. Results from studies in guinea pigs exposed to alternating PO_2 of 3.0 ATA and 0.2 ATA, and in man exposed to 20 minutes of oxygen at 2.0 ATA alternating with 5 minutes of normoxic breathing showed that the periodic interruption of hyperoxic exposure significantly extended oxygen tolerance [41,42]. From these studies, Lambertsen constructed a curve predicting oxygen tolerance extension by periodic interruption of hyperoxic exposure (Fig. 4-7)[35]. The solid line in Fig. 4-7 represents a 5% reduction in VC from continuously breathing oxygen. The broken line is a hypothetical curve for alternating 20 minutes of

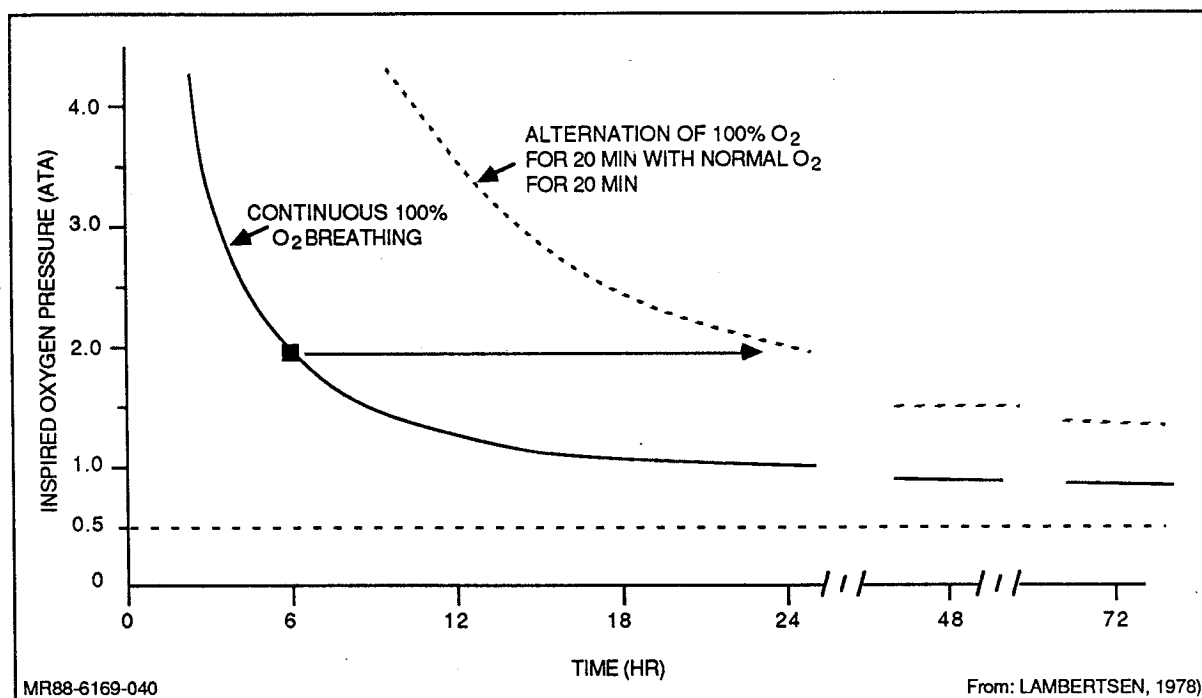


Fig. 4-7 Prediction of Oxygen Tolerance Extension by Periodic Interruption of Oxygen Exposure

breathing 100% oxygen with 20 minutes of breathing a normal PO_2 . These curves emphasize the large practical advantage of programmed, intermittent oxygen exposure in extending oxygen tolerance.

The usefulness of intermittent oxygen exposure to protect against oxygen toxicity is readily applied in hyperbaric medicine. However, is oxygen tolerance extension applicable to 8 hours of hyperoxia followed by at least 16 hours of normoxia every day (8 hours EVA per 24 hours)? In other words, are the effects of hyperoxia on different tissues and organs sufficiently pronounced to affect EVA, do they have a lasting effect, and are the effects detrimental? These questions need to be answered before effective EVA scenarios can be developed.

Although the acute pulmonary effects of breathing a high PO_2 are readily reversible upon return to normoxic conditions, long term pulmonary effects of repeated exposure over time have not been studied in detail. MacIntyre (1971) found no significant differences in VC or in forced expiratory volume in the first second (FEV_1) or peak flow (PF) in a group of 42 nonsmoker Naval Aviators divided into a non-tactical jet and tactical jet group [43]. Naval Aviator tactical jet pilots

breathe 100% oxygen throughout the duration of their flights. There were significant decreases in the maximum mid-expiratory flow rate (MMF), the expiratory flow rate for the first 200-1200 cc of the VC (MWF), the FEV_1/VC ratio and the MMF/VC ratio in the tactical jet aviator group. However, the values from both groups were within normal clinical ranges [44]. In addition, there have been no studies to determine whether or not tactical jet aviators have a higher incidence of obstructive lung disease later in life. Diminished MMF and MEF are sensitive indicators of peripheral airway dysfunction [45,46]. Many investigators believe that the first anatomical changes from chronic obstructive lung disease appear in the small airways, often years before symptoms and obvious pathologies develop [47,48].

In an attempt to quantify pulmonary oxygen toxicity, Lambertsen's group at the University of Pennsylvania, developed a procedure for calculating the dose of oxygen resulting in pulmonary toxicity [49]. When used in hyperbaric oxygen treatment for decompression sickness, they found that the total oxygen exposure should be limited to a Unit Pulmonary Toxicity Dose (UPTD) of 615 or less. In the extreme (serious decompression sickness cases responding poorly to hyperbaric oxygen (HBO) treatment), the limit of oxygen exposure was raised to 1425 UPTD. Using a simplified arithmetic method for calculating UPTD, an eight-hour exposure to an 8 psi PO_2 yields a UPTD of 26. At 10 psi PO_2 the UPTD is 141 - well below the limit of 615 used as a guideline in HBO treatment of decompression sickness. The equation for calculating UPTD is shown below:

$$UPTD = t(0.5/P - 0.5)^{-1.2}$$

- where:
- 1) t = time in minutes breathing hyperbaric oxygen. In this case, 480 minutes (8 hours).
 - 2) $P = PO_2$. In this case 0.54 ATA (8 psi) or 0.68 ATA (10 psi).
 - 3) 0.5 is the PO_2 at which a 50% incidence of a 2% decrease in vital capacity becomes asymptotic (see Fig. 4-5).
 - 4) -1.2 is the slope of the 2% delta curve (noted in 3) above on a log-log plot.

4.3.2 Circulating Red Blood Cell Mass

In addition to the effects of high oxygen tensions on the lungs, the effect on the circulating red blood cell mass (RCM) has attracted much attention. Johnson

(1983) wrote an excellent review on the effects of weightlessness on erythropoiesis [30]. In his review, he found a decrease RCM during weightless flight does not appear to result from a decrease in the mean red blood cell volume, but from decreased erythropoiesis. Because the PO_2 for the Gemini and Apollo flights was high (0.34 ATA or 5 psia), and hyperoxia is known to cause hemolysis of red blood cells, data from these flights does not unequivocally demonstrate that the decrease in RCM was due to a decreased erythropoiesis alone. Johnson reviewed NASA studies to delineate the role of microgravity and hyperoxia as causal factors for the decrease in RCM. These studies seemed to prove that hyperoxia (>0.34 ATA PO_2) over time will cause a 2.7% decrease in the circulating RCM; however, this decrease is less than that seen in the Skylab missions. Furthermore, the time for recovery of the RCM was longer after the shorter (28-day) Skylab mission than it was following the longer (84-day) mission.

Johnson used as evidence against hemolysis as being the cause of the decrease in RCM, the fact that the mean ^{51}Cr RBC halftime and mean RBC life-span were unaffected. Additional evidence against hemolysis as being the cause of decreased RCM in weightless, normoxic flights is the finding that the reticulocyte counts of the nine Skylab crewmembers were lower postflight (on the day following recovery) than preflight, except for two crewmembers of the 84-day mission who had higher postflight reticulocyte counts. Johnson further stated that, "Taken together, the Skylab and USSR data indicate that during space flight the RCM decreases, and this cannot be related to hyperoxia since the hyperoxic exposure of the Skylab crew members was of short duration prior to lift-off, and the USSR cosmonauts are not exposed to a hyperoxic environment. After the long duration missions, there was a delay between the time the crewmen returned to Earth and the return of their RCM to preflight levels. This delay, combined with the noted decrease in the reticulocyte numbers, suggests that the basic mechanism for the change is bone marrow inhibition." The first three Shuttle flights were of short duration (less than three days and normoxic), but the mean hematological changes, though slight, were in the "right direction" to further substantiate a decrease in RCM. However, the reticulocyte numbers were not decreased postflight. Therefore, hamatological data from these flights cannot be used as evidence for bone marrow inhibition versus hemolysis as the cause for decreased RCM in space flights.

Johnson postulated three plausible causes of bone marrow inhibition in weightless flight: (1) Inadequate caloric or protein intake, (2) Relative increase in the

total body hematocrit as a result of the early in-flight decrease in plasma volume, and (3) A shift in the hemoglobin P_{50} as a result of an increased plasma phosphorus. The latter shifts the oxyhemoglobin disassociation curve, resulting in a reduced affinity of hemoglobin for oxygen.

Only limited research has been conducted on the effects of hyperoxic exposure during EVA scenarios. Hendler (1974) recorded physiological and biochemical responses to intermittent oxygen and exercise exposures in three healthy adult males exposed to 8 psia PO_2 in a low pressure chamber [32]. On each of 14 days, subjects performed moderate physical activity averaging 249 kcal/h during 4 hours of the 8-hour exposure per day. A decrease in VC, along with significant changes in other pulmonary parameters, were noted. All the subjects subsequently reported that after 16 hours they felt fully recovered from the effects of the preceding 8-hour hyperoxic exposure. Hendler also measured a gradual decrease in red blood cell count (an average decrease of 8.38% on the 14th and last day of the hyperoxic exposure), hemoglobin concentration (an average decrease of 6.53%), and hematocrit (an average decrease of 9.15%). These parameters returned to normal 2 to 4 days after the 14-day interrupted exposure. In addition, a limited reticulocytosis occurred 2 days after the 14-day exposure. The changes in blood parameters noted are not considered pathological, but rather an anticipated physiologic response to hyperoxia mediated by a suppression of erythropoiesis and an accelerated destruction of older, more fragile red blood cells. Though these blood changes can be considered a form of oxygen toxicity, they were readily reversible. For example, Lambertsen (1978) found that in spite of a reduction of erythropoiesis in man exposed to 0.3 ATA PO_2 (with no signs of pulmonary oxygen poisoning developing), the stem cell and erythroid precursor pool is evidently unharmed by this level of PO_2 [35]. These cells were released from suppression when the hyperoxic exposure was terminated. Lambertsen's and Hendler's studies seem to substantiate the finding that hyperoxia, per se, will cause a decrease in RCM. Therefore, the question to be resolved is whether or not the decrease in RCM caused by hyperoxia will be additive or synergistic to that caused by weightlessness.

In the final analysis, Johnson (1983) stressed that, "The mechanism by which the change in RCM occurs is not yet known..." beyond the fact that it is due to a decreased erythropoiesis (bone marrow inhibition) [30]. In summary he stated that, "much has been learned of the in-flight RCM decrease, but the cause in the human

has yet to be proven to be absence of gravitational force - the mechanism by which it occurs is also unproven. From what is known, we can predict that every crew member will lose part of his measurable RCM during space flight. This loss of circulating red blood cells will be made up post-mission by a postflight stimulation of the bone marrow. This stimulation will last long enough to return the RCM to normal. No residual ill effect is known to remain. Whether this decrease in RCM, and later increase in bone marrow function, will be correlatable with eventual pathology is now unknown."

4.4 EXPOSURE TO 8 PLUS PSIA PO_2 DURING EVA

At present, it is not known whether an intermittent exposure to a single gas space suit pressure in the range of 8 to 9.5 psia can be safely tolerated during EVA missions projected in the Space Station Program. Three EVA possible scenarios are shown in Fig. 4-8 and 4-9 [50]. Scenarios I and II are theoretical projections in which the crewmember would spend 24 hours per week in EVA for a total of 312 hours during a 90-day mission. This is 6 hours per week more than projected by NASA in their Request for Proposal for an EVA design requirements study (NASA RFP 9BE2-72-4-37P, JSC, Sep 1984). Scenario III presents a more realistic EVA schedule prepared by Grumman Space Systems Division as part of a Design Reference Mission. In this scenario, the average weekly time spent in EVA is 18.6 hours, with a range of 12.0 to 29.5 hours per week. In every instance, at least 16 hours of breathing air at 1 ATA (0.2 ATA PO_2) is interposed between EVA evolutions.

In keeping with these scenarios the question arises, will the EVA crewmember have problems secondary to breathing oxygen at a PO_2 of 14.7 psia or less? This question was asked of two experts in the field of HBO therapy; Jared M. Dunn, M.D., San Antonio, Texas and James M. Clark, M.D., Ph.D., University of Pennsylvania Medical Center. Dr. Dunn felt that barring the fact that some individuals are more sensitive than others to the effects of increased PO_2 , the scenarios represented by Fig. 4-8 (Scenarios I and II), are safe, and "essentially complete recovery occurs by 24 hours." He further stated that "the simplicity, and thus reliability of the one-gas suit would justify any increased risk that the increased PO_2 presents." Dr. Clark felt that the probability of pulmonary oxygen toxicity occurring in any of the three scenarios is very low due to the time allowed for recovery after EVA (even 16 hours Scenario I).

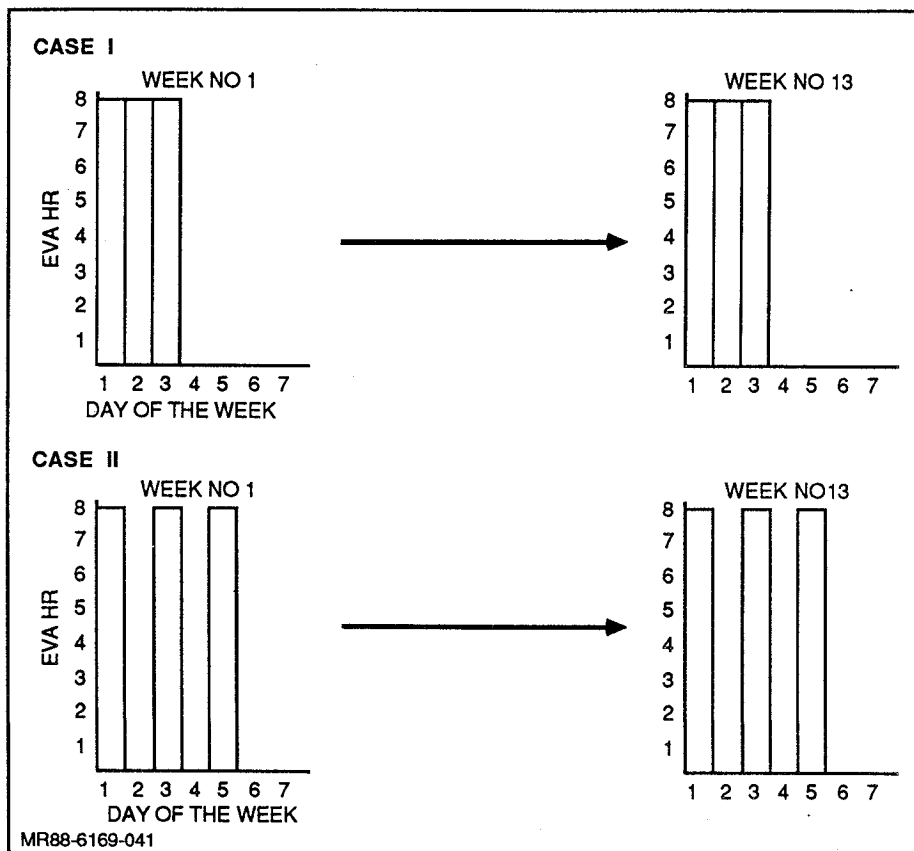
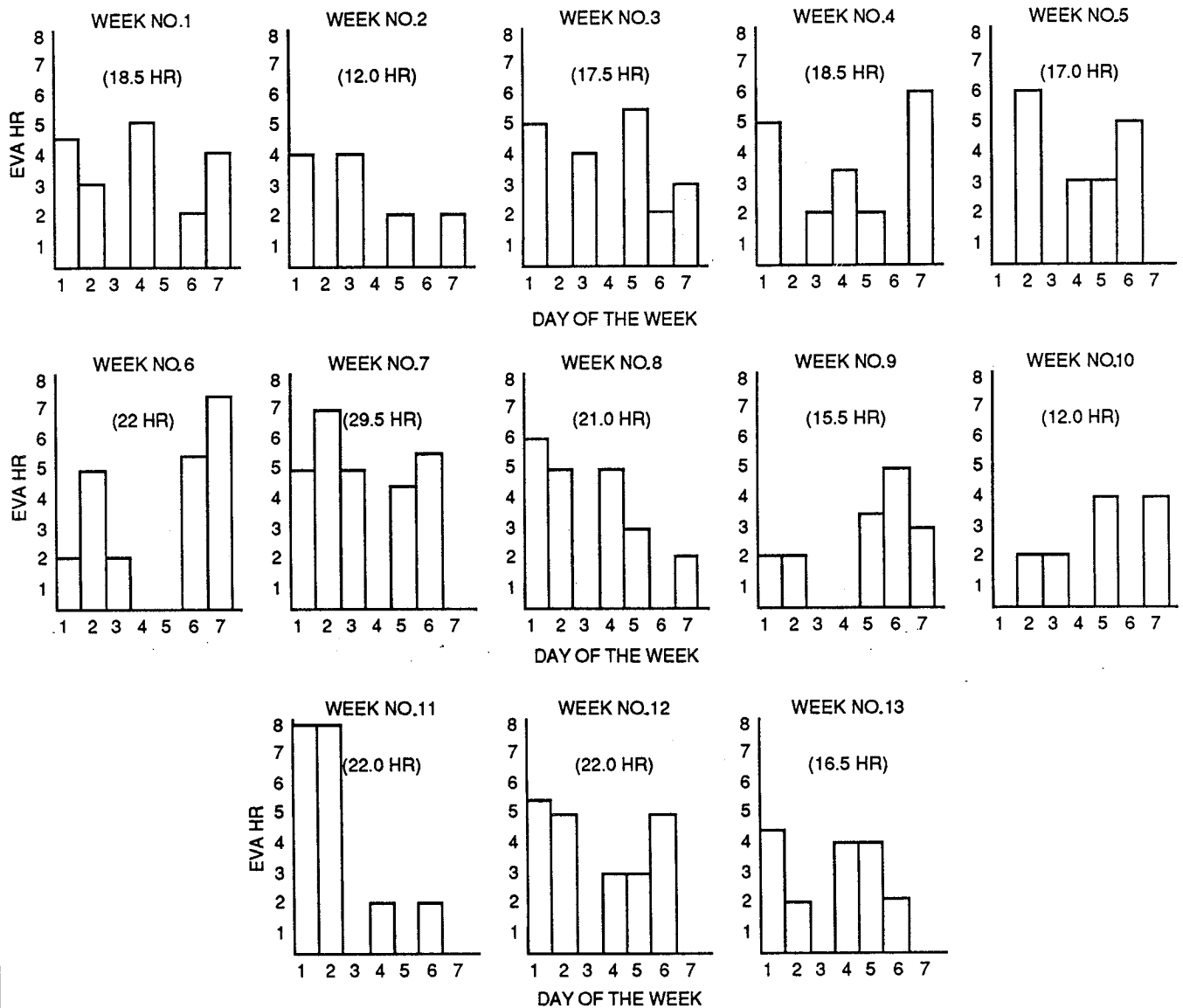


Fig. 4-8 EVA Schedules, Case I & II

It is interesting to note that Dunn (1962) in studying psychomotor performance under varying partial pressures of oxygen and nitrogen, noted an increase in task performance during 4 hours exposure to an increasing PO_2 up to 0.6 ATA (8.8 psia) [51]. According to Dunn this mitigative effect of oxygen enriched air upon proficiency decrement has also been noted by other [52,53].

The EVA scenarios presented in Fig. 4-8 and 4-9 assume that the PO_2 in the suit is 8 psia at the beginning of EVA. In fact, the suit will initially contain the same atmosphere (presumed to be air at 1 ATA) as the Space Station. The PO_2 in the suit will rise as oxygen is added to the suit to counter suit leakage or during purge operations. Figure 4-10 shows the increase in suit PO_2 as 100% oxygen replaces gas lost due to suit leakage. At a leakage rate of 55.69 scc/min, the PO_2 in the suit will reach 6 psia in 8 hours. If the leakage rate is greater than 55.69 scc/min, then in an 8-hour EVA evolution, the PO_2 will exceed 6 psia PO_2 . Technically, in an 8 psia suit, the PO_2 will never reach 8 psia - only approach it asymptotically.

CASE III



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Fig. 4-9 EVA Schedules, Case III

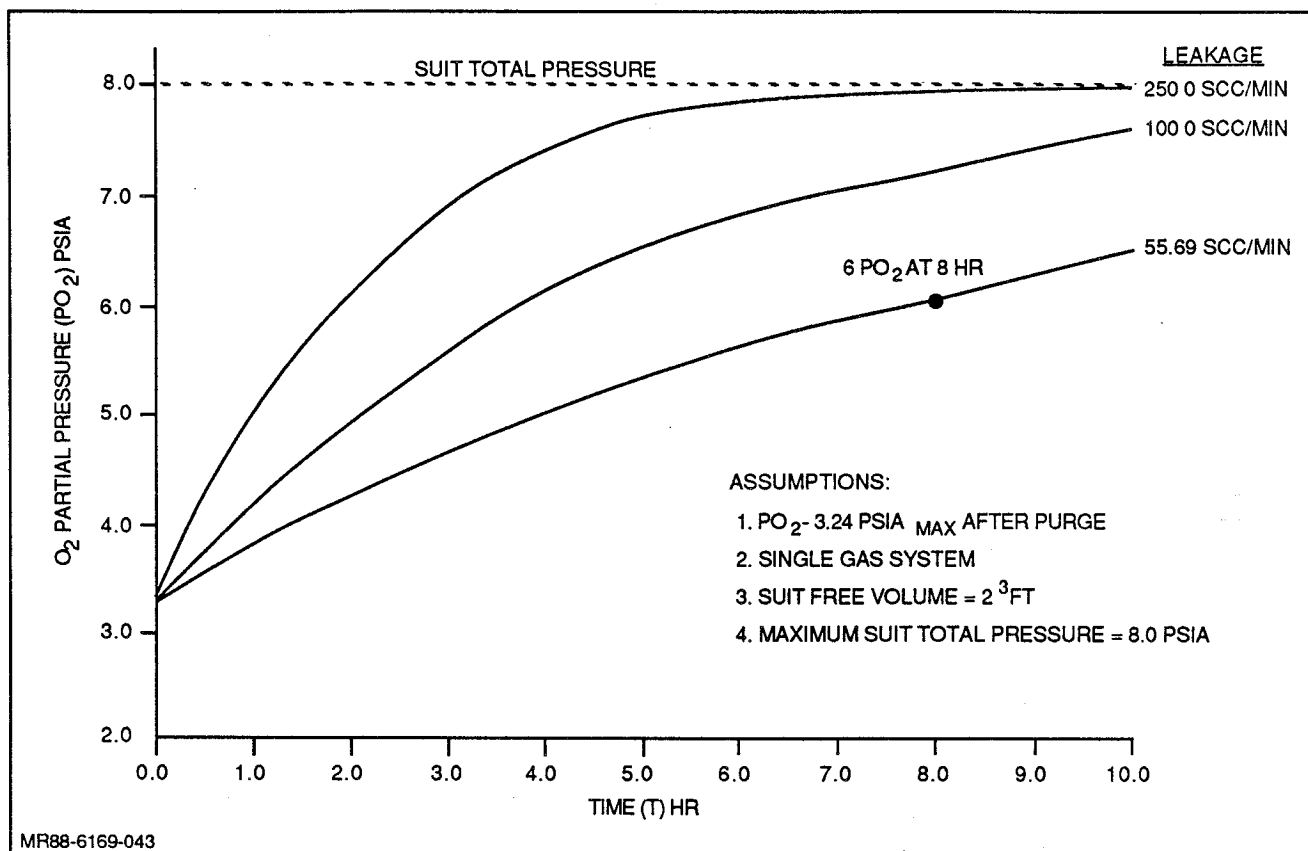


Fig. 4-10 Increase in Suit PO₂ as 100% O₂ Replaces Suit Leakage

4.5 SUMMARY

The limit of hypoxia that corresponds to "mild hypoxia" is not exact, and is based on performance standards defined by a particular user (or industry). Performance standards are in turn, based on what measures are used to define the hypoxic effects. However, it appears that the more recent research on this matter performed by Fowler et al gives a more accurate estimate of the threshold of decrement of performance due to hypoxia - in the one-g environment.

The early signs and symptoms of oxygen toxicity relate primarily to pulmonary toxic effects as readily observed by a decrease in lung vital capacity. At 8 psi PO₂, the effects from hyperoxic exposure for 8 hours or less represents acute physiological effects that are readily reversible upon return to normoxic conditions. Therefore, pulmonary oxygen toxicity is not adjudged to be a problem in conjunction with anticipated Space Station EVA missions in an 8 psia space suit.

The probability of an EVA mission lasting (or exceeding) 8 hours is low. The peak PO_2 in the space suit will only be 7.3 psi with a range of 6.8 psi for 3 hours to 7.8 psi for 6 hours at an estimated suit leakage rate of 250 scc/min. For an 8 psia single-gas space suit, the PO_2 will, in fact, not reach 8 psia, as would be the case if the oxygen were delivered to the astronaut via an oronasal mask.

Both weightlessness and breathing hyperbaric oxygen decrease the circulating red blood cell mass. It is not known, however, to what extent this decrease can be attributed to hyperoxia per se.

4.6 RECOMMENDATIONS FOR FURTHER STUDIES

- Studies during weightless flight to determine effects of microgravity induced changes, e.g., fluid shifts, etc, on mild hypoxic states
- Examine engineering trade-offs, e.g., avionics cooling, etc, on pressures of 9.0 to 9.5 psia and higher oxygen percentages
- Examine effects of drugs used for Space Adaptation Syndrome protection on mild hypoxic states
- Examine metabolic enhancers - nootropic drug effects on mild hypoxia
- Conduct studies, at simulated EVA workloads in a one-g environment, on the effect of breathing oxygen for up to 8 hours per 24 hours on circulating red blood cell mass for 90 days, or until an effect on the RCM can be shown to reach a steady state
- Compare RCM of IVA crewmembers to EVA crewmembers during Space Station 90-day missions.

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5 - CARBON DIOXIDE LEVELS

This section is in response to Section 2.9 in the RFP as an additional subject pertinent to EVA, and was prepared by Dr. Paul A. Furr and Dr. William J. Sears.

5.1 INTRODUCTION

Hypercapnia will result if a failure in the Extravehicular Maneuvering Unit (EMU) carbon dioxide removal system occurs. The effects of hypercapnia in turn, is a function of the arterial partial pressure of carbon dioxide (PaCO_2) and the duration of exposure. Acute reactions to breathing an increased fraction of carbon dioxide in the inspired air (partial pressure of inspired carbon dioxide - PICO_2) include an increase in heart rate and respiratory minute volume. These effects are caused by sensitive chemoreceptors (primarily the chemoreceptors in the central nervous system) and sympathetic nervous system stimulation. Most of the carbon dioxide in the blood is in the form of bicarbonate ion, and as the level of carbon dioxide increases, the acid-base balance is disturbed resulting in an acidosis. Altered alveolar partial pressures of oxygen (PAO_2) and carbon dioxide (PACO_2) can combine to affect performance.

In addition to physiological effects, there is recent evidence that carbon dioxide may be involved in the initiation of bubble formation in the pathogenesis of decompression sickness because of its high solubility and rate of diffusion (20 times that of oxygen). If correct, carbon dioxide control in the EMU takes on added importance.

The question addressed here is: During EVA, what level of carbon dioxide should be tolerated?

5.2 CARBON DIOXIDE PRODUCTION DURING EVA

Though man is normally exposed to low concentrations of carbon dioxide in his Earth environment, it is quite certain that he can live indefinitely in an atmosphere entirely free of the gas, for he produces and excretes more than enough to meet his physiologic demands. Most of the 400 to 800 liters of carbon dioxide produced by an

active person each day is excreted through the lungs, the remainder appears in the urine as bicarbonate ion.

The amount of carbon dioxide produced during EVA will be a function of diet and physical activity.

5.2.1 Diet

Because of inherent chemical differences in the composition of carbohydrates, fats and proteins, different amounts of oxygen are required to oxidize completely the carbon and hydrogen atoms in these foods. For carbohydrates, the Respiratory Quotient (RQ) is 1.00. Since fats contain fewer oxygen atoms in proportion to atoms of carbon and hydrogen, more oxygen is required to oxidize fat to carbon dioxide and water. For example, when palmitic acid, a typical fatty acid, is oxidized to carbon dioxide and water, 16 carbon dioxide molecules are produced for every 23 oxygen molecules consumed giving a RQ of 0.696. Protein, on the other hand, is not simply oxidized to carbon dioxide and water during metabolism. It is first deaminated with the nitrogen and sulfur fragments for the most part, being excreted. The resulting "keto acid" fragments are then oxidized to carbon dioxide and water and, as is the case for fatty acids, these short chain keto acids require more oxygen for complete combustion in relation to carbon dioxide produced. The RQ for the protein albumin is 0.818 [1].

The calculation of RQ is based on the assumption that the exchange of oxygen and carbon dioxide measured at the lungs reflects the actual gas exchange in the cell. Under steady rate exercise conditions this assumption is reasonably valid [1]. Factors that disturb the normal metabolic relationship between these gases, however, may spuriously alter this exchange ratio. Respiratory physiologists have termed the ratio of carbon dioxide produced to oxygen consumed under such conditions, when the exchange of oxygen and carbon dioxide at the lungs no longer reflects the oxidation of specific foods in the cells, the Respiratory Exchange Ratio (R) - even though this ratio is calculated in exactly the same manner as the RQ.

5.2.2 Physical Activity

Man produces carbon dioxide at rates which vary from 0.2 L/min during rest to as high as 5 L/min during heavy exercise. At rest, $R = 0.85$. During exercise it

may exceed 1.0 for short periods. Examples of energy expenditure, and therefore oxygen consumption and carbon dioxide production, are given in Table 5-1 [2].

The maximum steady-state energy output for a person in good physical condition is in the order of $350 \text{ kcal/m}^2/\text{h}$, a factor of 10 greater than the minimum rate during sleep. Metabolic rates two to three times the steady state maximum are possible for short periods. Females generally have about a 10% lower metabolic rate under standard conditions than males of the same age and size [2]. Horrigan & Waligora reported that metabolic energy expenditure rates during Skylab EVA averaged 230 kcal/h . Rates as high as 351 kcal/h were measured during Apollo lunar surface EVA (one-sixth Earth gravity) [3]. These authors concluded that the capability to work at relatively high levels (up to 500 kcal/h when required) was demonstrated without physiological problems provided the life support capability is adequate. They also noted that the average energy cost of long EVAs was remarkably consistent at about 200 to 250 kcal/h , and that it appeared to be a

Table 5-1 Energy Expenditure for Various Activities*

	kcal/m²/hr	kcal per person per hr	Oxygen consumption liters/hr	Carbon Dioxide production liters/hr
REST				
• Sleeping	35	63	13.1	11.1
• Sitting upright	50	90	18.7	15.9
LIGHT ACTIVITY				
• Standing	85	153	31.7	26.9
MODERATE ACTIVITY				
• Walking (3 mph)	140	252	52.3	44.5
HEAVY ACTIVITY				
• Bicycling	250	450	93.4	79.4
• Swimming	350	630	130.7	111.1
• Skiing	500	900	186.7	158.7
• Running	600	1080	224.1	190.5
<p>*The following assumptions have been made in deriving Table 5-1:</p> <p>(1) 1.8 m^2 surface area for the average man.</p> <p>(2) 4.82 kcal generated for every liter of oxygen consumed.</p> <p>(3) Ratio of carbon dioxide produced to oxygen consumed = 0.85.</p>				
R88-6169-045				

function of the crew pacing their activity rather than to the effort involved in performing individual tasks. More recently, Horrigan presented data showing that the average metabolic energy expenditure rate during Shuttle EVAs was slightly less than 200 kcal/h [4].

5.3 PRESENT EMU PRIMARY LIFE SUPPORT SYSTEM (PLSS)

The carbon dioxide sensor in the present EMU is located in the ventilation loop downstream to the point where makeup oxygen is added to the loop and thus, does not measure the actual partial pressure of carbon dioxide (PICO_2) of the inspired gas. It has a range of 1 to 30 mm Hg, and a audio and visual alarm if the PICO_2 reaches 2 mm Hg. The range of sensitivity of the sensor is $\pm 5\%$ at less than 2 mm Hg, $\pm 2.5\%$ between 2 and 10 mm Hg and $\pm 5\%$ between 10 and 30 mm Hg. The current NASA medical requirements call for a PICO_2 limit of 15 mm Hg. However, from an operational point of view if the PICO_2 becomes elevated in the EMU, and it cannot be attributed to an increased metabolism, it must be assumed that there is a malfunction of the PLSS. Such an event may be sufficient grounds for terminating the EVA even though 15 mm Hg PICO_2 can be easily tolerated. A 15 mm Hg PICO_2 is equivalent to 2.0% carbon dioxide at sea level barometric pressure.

5.4 ACUTE EFFECT OF BREATHING A GAS ENRICHED WITH CARBON DIOXIDE

The acute effect of breathing a gas containing increasing amounts of carbon dioxide is an increase in respiratory minute volume due predominantly to an increase in tidal volume, Fig. 5-1 [5,6]. In a study by White et al in 1952 of human tolerance to acute exposure to carbon dioxide, 31 men (21 to 43 years of age) were exposed to a 16 minute period of 45.6 mm Hg PICO_2 (6% CO_2) [7]. As a result, the respiratory rate, expiratory volume and alveolar carbon dioxide concentration increased. In spite of these physiological changes, there was no decrease in ability to perform a card-sorting behavioral test.

In a recent study conducted by Askanazi et al in 1979, breathing patterns were examined in 25 men and 5 women during 10 minutes of exposure to 15.2, 22.8 and 30.4 mm Hg PICO_2 [8]. At these carbon dioxide tensions there was an increase in respiratory minute volume. Although carbon dioxide tolerance was not assessed in this study, the subjects were able to easily withstand the increased carbon dioxide levels.

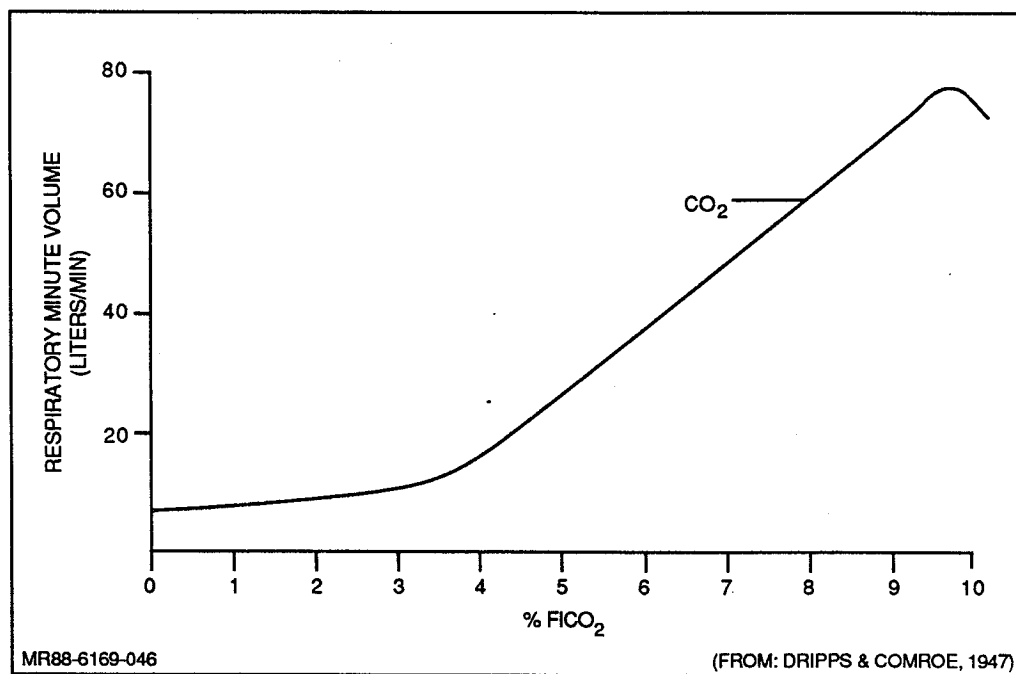


Fig. 5-1 The Response of Awake, Healthy Men to Inhalation of Increasing Concentration of CO₂ in Air

Finally, in an exhaustive review by NIOSH of many studies of carbon dioxide tolerance during exercise, the effects on metabolism and ventilatory responses were readily apparent only at PICO₂'s of at least 21.3 mm Hg [9]. Furthermore, the NIOSH authors concluded that all grades of exercise, including exhaustive stress (214.8 kcal/h above baseline), can be tolerated for at least 30 minutes at carbon dioxide concentrations of up to 4% (30.4 mm Hg); and at or below 2.8% carbon dioxide concomitant with lower, but still strenuous levels of exercise (111.6 to 154.8 kcal/h), no ill effects other than awareness of increased ventilation (no dyspnea reported) were experienced by the subjects.

5.5 CHRONIC EFFECTS OF BREATHING ELEVATED LEVELS OF CARBON DIOXIDE

Glatte et al in 1967 showed that studies on humans indicated that compensation for acidosis caused by continuous exposure to 11.4 mm Hg PICO₂ will take approximately 23 days [10]. During the uncompensated period, a decreased pH, lowered plasma calcium and inorganic phosphorus, decreased pulmonary excretion of carbon dioxide, and decreased bicarbonate excretion by the kidneys occurs. The compensated phase (day 24 to 42) was characterized by a return of the blood pH to normal, a rise in urinary pH, increases in PACO₂, bicarbonate excretion, and increases in plasma calcium and inorganic phosphorus. During a 5-day exposure to 22.8 mm Hg

PICO₂, the authors stated that the changes were not indicative of a serious challenge. A decrease in pH accompanied by an increase in serum bicarbonate was observed within the first 2 days. Although some aspects of this study were hampered by its short duration, the data does indicate that the body apparently compensates readily to the high carbon dioxide level. An immediate physiological response to 22.8 mm Hg PICO₂ was also indicated in a study on intermittent exposure.

In contrast, Messier et al in 1979 showed that continuous exposure to 6.2 to 9.3 mm Hg PICO₂ indicated that renal compensation was not apparent until after the third week of exposure, when carbon dioxide was dumped from bone stores, increasing the concentration sufficiently to trigger compensatory mechanisms [11].

The effects of 30 to 42 days of continuous exposure to 7.6 mm Hg and 15.2 mm Hg PICO₂'s were studied in submarine crews during actual operations and in subjects under laboratory conditions [12,13]. The effects of carbon dioxide exposure under these conditions included increases in minute ventilation, tidal volume, PACO₂, oxygen uptake and physiological dead space. There was also a persistent respiratory acidosis and cyclic changes in pH that appeared to be related to cyclic changes in carbon dioxide absorption from bone. These changes apparently did not interfere with the ability of the submarine crew or the laboratory subjects to perform various assigned tasks. Likewise, physiological changes associated with a 5-day exposure to 22.8 mm Hg PICO₂ were found not to be a serious challenge. Indeed, at this PICO₂, the body more readily adjusts than it does to lower levels of carbon dioxide [9].

Van Ypersele de Strihou et al [14] in 1966 constructed a carbon dioxide response curve for humans made hypercapnic by chronic pulmonary insufficiency. They studied the acid-base balance on 420 patients over a five-year period and compared the results to Schwartz et al [15], who the year before, studied dogs chronically adapted to hypercapnia. The results were virtually identical. Van Ypersele de Strihou et al and Schwartz et al established that in chronic carbon dioxide exposure mean plasma bicarbonate concentration rises in a curvilinear fashion as PaCO₂ increases from normal to 77 mm Hg. Hydrogen ion concentration on the other hand increases linearly with increasing PaCO₂. The significant point here is that given time, the kidney, by generating bicarbonate, compensates for what would otherwise be a decrease in blood pH associated with hypercapnia.

Evidence regarding the effects of chronic exposure to carbon dioxide at a PICO_2 of 7.6 mm Hg (1%) is limited. The effects discussed include increases in alveolar dead space at PICO_2 's of 6.1 and 6.8 mm Hg [16,17] and cyclic calcium tides corresponding to alternate bone storage and release of carbon dioxide during exposure to 6.1 to 9.1 mm Hg PICO_2 [11]. The significance, if any, of these changes remains to be determined. The majority of the available human data deals with continuous exposures of 11.4 to 22.8 mm Hg PICO_2 's in which it has been adequately demonstrated that observed changes are limited to normal renal and respiratory compensatory mechanisms without any apparent adverse symptoms. Adaptive mechanisms involving reduced responses to the respiratory, and possibly to the cardiovascular effects of carbon dioxide, provide an additional safety margin during prolonged exposure. Although the absence of specific data relating to intermittent exposures may limit the reliability of the data obtained from continuous-exposure studies, the available evidence indicates that even a prolonged, continuous-exposure to 22.8 mm Hg PICO_2 presents no apparent problems during normal activity in specially conditioned and physically fit subjects in a one-g, Earth normal environment.

In 1982 the Naval Submarine Medical Research Laboratory (NSMRL) published a position paper on the toxic effects of chronic exposure to low levels of carbon dioxide based on human studies (submarine patrols) and animal studies [18]. Their review of the effects of short-term exposures to carbon dioxide is summarized in Fig. 5-2, and represents their "official judgement" on the hazards of carbon dioxide. No such figure exists for responses to long-term carbon dioxide exposure. However, the Navy's policies regarding long-term exposures are:

- 0.5% to 0.8% - There is probably no significant effect on the body
- 0.85 to 3.0% - Prolonged exposure could induce impairment of mental functions and slowing of physical activities
- 3.0% and above - Further impairment of mental functions and slowing of physical activities occur.

NSMRL's position regarding exposure to low-level carbon dioxide (PICO_2 of 10 torr and 40 days) after an extensive literature review is: "Physiological responses to the CO_2 environment were repeatedly documented, but toxic effects were not apparent. Human exposures have been safely conducted in atmospheres containing up to 5 torr CO_2 , for up to 90 days. Such exposures are therefore considered safe at this time."

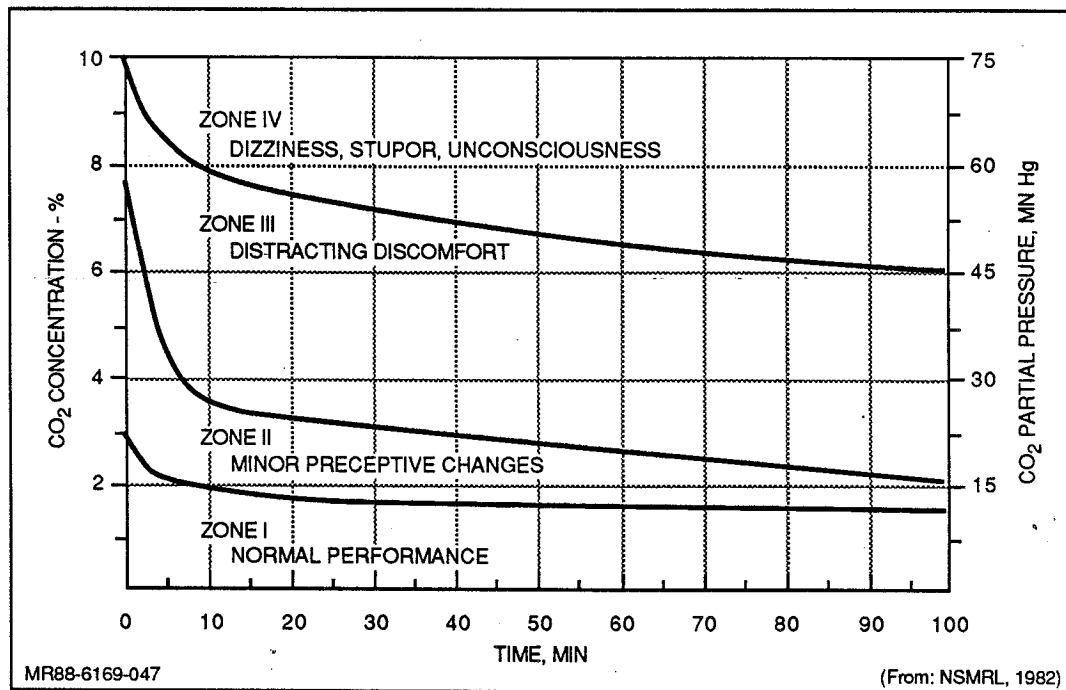


Fig. 5-2 U.S. Navy's Official Judgement on the Hazards of Short-Term Exposures to CO₂

Part of NSMRL's review concerning low-level carbon dioxide effects on humans is reproduced as Appendix B. Of particular interest to the astronaut are the "secondary effects" of low-level carbon dioxide on bone and metabolism, to wit:

"The urinary excretion of hydroxyproline, plasma concentration of calcitonin, and plasma concentration of parathormone tended to 'not change.' Decrements of vitamin D concentration in plasma have been measured (See Appendix B, Table 2e)." "The metabolism tended to 'not change' as evidenced by a few studies showing 'no change' of the body temperature, daily intake of food, fecal wet-weight, fecal dry-weight, fecal nitrogen excretion, and nitrogen balance (See Appendix B, Table 2f). Possible 'changes' were noted in the respiratory exchange ratio, oxygen uptake, ventilatory excretion of carbon dioxide, and the urinary excretion of nitrogen. Possibilities of 'no change' were also found for the plasma concentration of cortisone, the reticulocyte count, and the white blood cell count. Possible 'change' occurred in the polymorphonuclear and eosinophile counts." The reader is referred to Appendix B for additional effects of low-level carbon dioxide.

5.6 EFFECTS OF BREATHING CARBON DIOXIDE DURING EXERCISE

In 1949 Schaefer [19] described an exercise study in which healthy subjects were exposed to 22.8 mm Hg PICO_2 for up to 8 days. He found that at the same PICO_2 , PACO_2 was higher during work after adaptation than it was during rest. The depth of breathing was reported to have decreased and the rate of respiration to have increased while the subjects worked during exposure to carbon dioxide. This results in increased oxygen intake and carbon dioxide excretion. Adaptation to the increased carbon dioxide level was apparent by decreased minute ventilation during work as well as resting; however, the work levels never decreased to the extent that the resting levels did. The author offered no information on the subjects' ability to tolerate the work plus the increased carbon dioxide atmosphere. All work was performed at 40 W (0.57 kcal/min) above a resting metabolic rate which would be equivalent to a moderate work situation where frequent breaks are essential. No untoward effects were reported at this work level.

The effects of breathing elevated PICO_2 's and exercise was the object of experiments reported by Menn et al [20,21]. In 1970 Menn et al exposed eight exercise-trained men to PICO_2 's of 8, 15, 21 or 30 mm Hg. The subjects engaged in 30 minutes of moderate and heavy exercise ($1/2$ and $2/3$ maximum $\dot{\text{V}}\text{O}_2$, respectively). At 8 and 15 mm Hg PICO_2 , there were no apparent difficulties in performing the exercise. Higher PICO_2 's caused some discomfort, but not of sufficient magnitude to prevent the subjects from exercising. Eight healthy men (age 18 to 21 years) were exposed to carbon dioxide at PICO_2 's of 7.6, 15.2, 21.3 and 29.6 mm Hg for 30 minutes while performing both steady-state and maximum-exertion tests in an upright position on a bicycle ergometer. The subjects had undergone a 14-day training period involving daily increased workloads. The workload was reported in Watts (W), 1 W being equivalent to 0.01433 kcal/min. The beginning load was 50 W (0.72 kcal/min); the maximum attained was 250 W (3.58 kcal/min). The study was performed in an environmental chamber with controlled carbon dioxide levels, temperature, and humidity. Respiratory rate, minute volume, rectal temperature, ECG, heart rate, blood pressure, PaCO_2 and PaO_2 were measured. All eight subjects completed all regimes at every carbon dioxide exposure level, with the exception of the maximum-exertion test at 29.6 mm Hg PICO_2 . No difficulty was reported at PICO_2 's below 21.3 mm Hg. At or above this level, the subjects reported respiratory symptoms during exercise performed at two-thirds maximum and at maximum oxygen uptake. Two subjects reported intercostal muscle pain secondary

to rate and depth of respiration incurred at 21.3 mm Hg PICO_2 . Three others reported that respiratory difficulties had impaired their performance at the same carbon dioxide level. At 29.6 mm Hg PICO_2 , six subjects reported mild-to-moderate frontal headaches. The headaches generally occurred near the end of the exercise period and were not severe enough to interfere with the subjects' performance. Increased PaCO_2 was linear and related to the PICO_2 .

Menn et al [20,21] also showed that hypercapnia combined with exercise causes a greater decrease in blood pH than does exercise alone. No greater burden was placed on the cardiovascular system than was seen in exercise alone. They concluded that humans can perform strenuous work for short periods without obvious stress, even at high carbon dioxide levels. In another exercise study, Craig et al [22] made use of inspiratory and expiratory resistances during exposure to 23.6 to 29.6 mm Hg PICO_2 to measure treadmill exhaustion limitations. Thirteen healthy men were tested on treadmill grades up to 22%. Inspiratory resistances ranged from 1.5 to 15.5 cm $\text{H}_2\text{O}/\text{L}/\text{sec}$, expiratory resistances from 2.0 and 3.9 cm $\text{H}_2\text{O}/\text{L}/\text{sec}$, and PICO_2 's ranged from 23.6 to 29.6 mm Hg. Measurements included tidal volume, heart rate, and inspiratory flow, as well as expired carbon dioxide levels. Exhaustion was the point at which the subject decided to end the routine. After 110 tests, results indicated that at the minimal inspiratory (1.5 cm $\text{H}_2\text{O}/\text{L}/\text{sec}$) and expiratory (2.0 cm $\text{H}_2\text{O}/\text{L}/\text{sec}$) resistance levels, only a PICO_2 in excess of 22.8 mm Hg consistently resulted in reduced endurance. At maximum inspiratory and minimum expiratory resistance, the range of 23.8 to 29.5 mm Hg PICO_2 did not appreciably change the subjects' endurance compared with that when the subjects breathed air.

Sinclair et al [23] also focused on the physiological response of the body during exercise to the inhalation of increased carbon dioxide concentrations. Four healthy men performed three levels of work (low, moderate, and heavy) in a chamber having a PICO_2 of 21.3 mm Hg. No equivalence in metabolic rates or oxygen consumption data were given by the authors, who used heart rate as a measure of workload. The effect on maximum oxygen uptake was not noted. Measurements were done in air after 1-hour exposures to acute and chronic (15 to 20 days) exposure to the gas. The individual exercised in a supine position on a bicycle ergometer twice daily for 45 minutes, separated by a 5-hour rest period. Arterial pH was lowered proportionally with increasing carbon dioxide exposure and exercise stress. Again, exercise compounded the acid-base problem (acidosis) of inhaling an elevated PICO_2 .

They concluded that carbon dioxide at tensions up to 21.3 mm Hg could be tolerated by normal subjects, both at rest and during strenuous, steady-state exercise. The authors reported the absence of cardiac abnormalities and contrasted their results with those of Menn et al above.

An exercise regimen in the previously cited paper by Glatte et al [10] offered similar data on the ability of six healthy subjects to tolerate work during exposure to 22.8 mm Hg PICO_2 . The 5-day exposure, as well as the 5-day pre-exposure and post-exposure control periods, included a steady, moderate exercise program involving two routines daily. Each routine was a 1-hour session on a bicycle ergometer equivalent of a heavy workload. The exercise was tolerated well by the subjects. In control periods, exercise produced a marked increase in minute ventilation averaging from 12.5 to 40.6 L/min; while during exposure to carbon dioxide, minute ventilation increased from an average of 18.3 to 67 L/min. Pulse rate increased to a maximum of 152 beats/min during the chronic exposure exercise period from a resting mean of 73 beats/min. The maximum attained during exercise in the control period was 145 beats/min from a resting mean of 69 beats/min.

Clark et al [24] further elucidated the effects of 9.8, 20.2, 30.0 and 39.8 mm Hg PICO_2 exposures when combined with an exercise program. Their exercise regime consisted of walking or running on a treadmill at a 10% grade at speeds of 1.8, 3.4, 4.8 and 6.0 mph for 6 minutes at each speed (without the treadmill stopping between speed adjustments). This 24-minute, 1.6 mile run was preceded and followed by resting control periods spent standing on the treadmill. The study was conducted in an environmental chamber providing controlled temperature and carbon dioxide levels. The subjects were nine healthy, young Air Force members who had just completed basic training and who also had participated in a 12-week pre-study exercise conditioning program. Even at the highest PICO_2 there were no changes in oxygen consumption; however, significant changes were seen in ventilatory response indices. There was an increase in minute volume from 10.13 +/- 1.84 L/min at rest with no inspired carbon dioxide to a maximum of 169.06 +/- 16.68 L/min at a maximum treadmill speed of 6.0 mph and 39.8 mm Hg PICO_2 . The measurements of acid-base balance confirmed the additive effects of respiratory acidosis caused by inspiring high PICO_2 's and of metabolic acidosis caused by increased carbon dioxide production secondary to exercise. The arterial pH, which dropped from about 7.41 at rest with no inspired carbon dioxide to 7.13 at maximum

exercise and PICO_2 , was associated with a ninefold increase in arterial lactic acid. A twofold rise in blood lactic acid occurred between 4.8 and 6.0 mph during the experiment. The subjects experienced significant symptoms during the study, including the collapse of three subjects at maximum exercise and PICO_2 , mental confusion, impaired vision (both central and peripheral), and severe headache (in the post-exercise period). Severe headache, dyspnea, and impaired central and peripheral vision were also reported during a special, single-subject study conducted at a treadmill speed of 6.5 mph and at 39.3 mm Hg PICO_2 for 8 minutes. The authors also observed that initial exposure at the highest PICO_2 's caused the most severe symptoms. Since all subjects were able to run at 8.0 mph while breathing air, and yet three collapsed at the highest PICO_2 while running at 6.0 mph, the authors surmised that changes in the intensity of either stressor would cause a reciprocal change in the subjects' ability to tolerate the other.

Luft et al [25] investigated the effects of exposure to 14.4 mm Hg PICO_2 combined with exercise. The study was divided into two parts. The first concerned exercise tolerance by 12 healthy men (mean age of 26.5 years). The subjects exercised on a bicycle ergometer at an initial workload of 49 W over baseline and subsequent workload increases of 12.2 W until the subjects could no longer maintain the pedaling rhythm. The initial resistance was maintained for 3 minutes with increases applied each minute thereafter. The exercise regimes were repeated in air at a PICO_2 of 15 ± 2.1 mm Hg. Consequently, each subject was his own control. At each submaximal workload, the mean heart rate and systolic blood pressure were slightly higher during exposure to carbon dioxide; however, the increase was not significant. The heart rate was lower than control at the end point. The pulmonary ventilatory measurements indicated that increased PICO_2 resulted in significantly increased minute ventilation at submaximal exercise levels. The increases were 40% to 50% above controls at all workloads except maximum, where the increase was only 2%. Other measurements included mean oxygen consumption and carbon dioxide elimination. The oxygen consumption was higher (though not significantly) at submaximal exercise and at increased PICO_2 's and significantly lower (-13%) at maximum exercise with carbon dioxide. In contrast, carbon dioxide elimination was lower during carbon dioxide exposure than during the control period.

In the second part of this study, 10 healthy men completed the same exercise routine while the PICO_2 was maintained 15.0 mm Hg. In this series, however, respiratory measurements were made prior to exercise, during maximum exercising, and during recovery. These observations showed lower oxygen consumption during the last 2 minutes of exercise and during the first minute of recovery than during carbon dioxide exposure. The effects on acid-base balance were evident in a decreased PaCO_2 during controlled, non carbon dioxide exposure exercising. This decrease lasted through the fourth minute of recovery. In contrast, during carbon dioxide exposure, the PaCO_2 rose during the final minute of exercise and dropped only slightly during the first minute of recovery. Bicarbonate, which also fell during the control exercise, was correlated by the authors with the buildup of blood acid metabolites. Blood electrolyte levels generally increased, peaking during the last minute of exercise. Potassium and phosphorus increased nearly 60%. The authors concluded that a PICO_2 of 15.0 mm Hg was sufficient to affect an individual's exercise capacity by altering the physiologic elimination of carbon dioxide. The metabolic acidosis caused by maximum exercise was not reduced by ventilation in the presence of a 15.0 mm Hg PICO_2 which was already burdening the ventilatory process.

5.7 BASIS FOR ESTABLISHING CARBON DIOXIDE LIMITS DURING EVA

Inhalation of carbon dioxide at tensions greater than 129.3 mm Hg (17% FICO_2) is life threatening and the effects appear rapidly. Loss of consciousness has been reported in less than 50 seconds during inhalation of between 129.3 and 228.0 mm Hg (17-30%) PICO_2 in all subjects exposed [26,27,28]. At PICO_2 's of 79.1 mm Hg (10.4%) for 3.8 minutes and 57.9 mm Hg (7.6%) for 7.4 minutes, loss of consciousness was observed by Dripps and Comroe [6] in 3 of 31, and 1 of 42 test subjects respectively. Symptoms reported at 76.0 mm Hg PICO_2 (10%) include eye flickering, psychomotor excitation, myoclonic twitching, headache, dizziness, dyspnea, sweating, restlessness and "fullness in the head" [7,29]. Schaefer [30] noted similar symptoms in humans exposed to the gas at 51.7 mm Hg PICO_2 (7.5%) for 15 minutes. The information provided by the aforementioned investigators indicate that dyspnea, dizziness, and headache are the predominant symptoms at or above 56.9 mm Hg PICO_2 . The only reported effect of brief exposure at lower concentrations was that of respiratory stimulation (see Fig. 5-1) [6]. A subjective awareness of increased ventilation with slight-to-moderate dyspnea on acute exposure to carbon dioxide has been reported at an average respiratory minute volume of 62.7

L/min (range 29-110 L/min) with marked dyspnea reported at 86.8 L/min (range 50-130 L/min) [6]. Subjects reporting no dyspnea had maximal minute volumes ranging from 22 to 114 L/min (average = 60 L/min) [22]. Upon inhalation at 57.9 mm Hg PICO_2 , respiratory minute volumes averaged 51.5 L/min (range 24-102 L/min); at 38.3 mm Hg PICO_2 , the average minute volume was 26 L/min; at 30.5 mm Hg it was 14 L/min; and at 22.8 mm Hg it was only 11 L/min. The resting respiratory minute volume for a normal young male is approximately 6 L/min. Although the reported data indicates a broad range of sensitivity to the respiratory stimulant effects of carbon dioxide, 22.8 mm Hg PICO_2 would not cause respiratory discomfort for even the most susceptible individuals.

A few investigators have indicated that cardiac abnormalities were observed during and after exposure to carbon dioxide [20,21,26,28,31]. Irregularities noted were minor and not necessarily predictive of the development of more serious complications. None of these abnormalities in cardiac function have been causally related to carbon dioxide exposures.

Storm and Giannetta [32] found no significant behavioral changes during continuous exposure to PICO_2 's below 30.5 mm Hg. However, a 1949 report by Schaefer [33] concerning chronic exposure to 22.8 mm Hg PICO_2 described stimulatory and depressant behavioral effects on the first 2 days. These results are contradictory to the more recently published studies [10,32,34] which give no similar indications of behavioral alterations at the same PICO_2 .

Numerous studies [10,19,31,35-38] have shown that continuous exposures to 11.4 - 22.8 mm Hg PICO_2 do not result in serious challenges to body function. In a 1951 article by Schaefer [39], cited as a basis for the present American Conference of Governmental Industrial Hygienists (ACGIH) standard, no significant symptomatic effects of 22.8 mm Hg PICO_2 were observed, although changes in pH and bicarbonate ion concentration, were apparent from chronic exposure. However, the decreased pH, increased bicarbonate ion concentration, and changes in other electrolyte levels represented evidence of normal physiologic response mechanisms. The same conclusions may be drawn from studies on respiratory function. Experiments conducted at PICO_2 's of 11.4 mm Hg for 42 days have demonstrated a propensity for tolerance, physiologic adaptation, and an absence of adverse effects [40-42].

Respiratory stimulation is indicative of a sensitive response mechanism and is apparent at all levels of carbon dioxide tensions above 7.8 mm Hg. The adaptation to the respiration-stimulating effects of carbon dioxide during continuous exposure is dramatically represented by a decreased response to a subsequent challenge to a higher PICO_2 . This apparent tolerance has been reported often [40,41,43]. The respiratory adaptation upon prolonged exposure to carbon dioxide is also characterized by improved oxygen utilization, more efficient carbon dioxide elimination, and an increased alkali reserve. These adjustments are related to similar changes in PACO_2 and to blood buffering activity. Evidence obtained in some studies suggests, although indirectly, that as homeostatic mechanisms achieve stability, the signs and symptoms of bodily reactions, such as changes in pulse rate and headache, begin to fade [10]. These adaptive changes seem to indicate that there is no irreparable damage or extreme challenge to the body. Continuous exposure to PICO_2 's of 11.4 to 22.8 mm Hg can be tolerated by healthy workers, even for prolonged periods, without untoward effects.

In the industrial setting, a worker might be required to perform work (e.g. physical exertion) at intensities between 0.5 kcal/min and 6.0 kcal/min throughout the day (30 kcal/h to 360 kcal/h above baseline). The effects of carbon dioxide on metabolism and ventilatory responses, although enhanced in these cases, begin to manifest themselves subjectively only when a PICO_2 of 21.3 mm Hg is reached [20,21]. Several studies [10,22,23,32] have indicated that all grades of exercise, including exhaustive stress (3.58 kcal/min above baseline) can be tolerated for at least 30 minutes at PICO_2 's up to 30.4 mm Hg. During inhalation of PICO_2 's ranging from 21.3 to 39.5 mm Hg at maximum exercise levels (2.58 to 3.58 kcal/min, attained on a bicycle ergometer or at treadmill speeds of 6 mph), healthy, trained subjects experienced respiratory difficulty, impaired vision, severe headache, and mental confusion [24]. Three subjects collapsed. At or below 21.3 mm Hg PICO_2 concomitant with lower, but still strenuous levels of exercise, no ill effects other than awareness of increased ventilation (no dyspnea reported) were experienced by the subjects [20,21]. Prolonged exposure at elevated PICO_2 's could result in attenuation of the effects enhanced by both exercise and simultaneous exposure to carbon dioxide [19], although even an individual previously unexposed to carbon dioxide can normally tolerate simultaneous 21.3 mm Hg PICO_2 inhalation and heavy exercise. In fact, it has been observed that training (as in the case of divers) or continuous

exposure to high PICO_2 's results in a lessened severity of signs and symptoms during both normal activity and moderate exercise [42].

5.8 CURRENT STANDARDS

NIOSH has recommended a time weighted average (TWA) concentration of 1% FICO_2 for a 10-hour workshift and a 40-hour workweek, with a ceiling limit of 3% for up to 10 minutes. Here, NIOSH is concerned that respiratory stimulation due to inhalation of carbon dioxide will result in an increased intake of other harmful, airborne chemicals which will probably not be the case during EVA. Exposure at or below the recommended TWA concentration of 1% FICO_2 will produce a minimal increase in respiratory minute volume (for an age group 20 to 59 years of age the normal minute volume is approximately 9 liters/min) [44]. In the EVA environment this TWA restriction (1% FICO_2) may not be applicable if it can be shown that the concentration of other airborne chemical contaminants are insignificant. Thus, the increase in respiratory minute ventilation caused by higher PICO_2 's would not cause inhalation of other, potentially harmful airborne chemicals.

In 1975, NASA [45] published limits for carbon dioxide for manned spacecraft air contaminants for several lengths of exposure. The highest allowable level of carbon dioxide was 4% (30.4 mm Hg PICO_2) for 10 minutes. Also listed were 3% (22.8 mm Hg PICO_2) for 60 minutes, and 1% (7.6 mm Hg PICO_2) for both 90-day and 6-month exposures. NASA, in its Skylab Flight Mission Rules [46], specified the maximum sustained FICO_2 for mission continuation as 1%, and the maximum emergency excursion allowable for a maximum of 3 hours as 1.9% (14.4 mm Hg PICO_2). These limits were based, in part, on experiments of continuous exposure [10] and on submarine studies [40,41], as well as on a compendium of many such related studies [6,10,33,37,40,41, 48-52]. The level was specified for continuous exposure in what must be considered a critical situation. It was also ascertained to be a level that would not cause significant deterioration of mental or psychomotor activity, as this would be most serious in manned space flight situations.

Schaefer's review [51] of the literature on human tolerance to chronic exposure to carbon dioxide suggests a triple tolerance approach. The author based his conclusions partly on previous submarine experiments [40,41] in which responses to various concentrations of carbon dioxide were identified. The resultant triple tolerance limit indicated that, at a level of 0.5 to 0.8% FICO_2 (3.8 to 6.1 mm Hg

PICO₂), no significant physiological, psychological, or adaptive changes occurred. No data were offered to indicate that there were effects over this range. At a 1.5% FICO₂ (11.4 mm Hg PICO₂) continuous exposure, performance and psychologic functioning were not adversely affected, although there were acid-base and electrolyte adaptations. At levels above 3% FICO₂ (22.8 mm Hg PICO₂), deterioration in performance may be expected, as may alterations in basic physiologic functions, such as blood pressure, pulse rate, and metabolism. Schaefer further stated that, although early regulations held that 22.8 mm Hg PICO₂ was permissible for submarine exposures, physiologic alterations identified at a 11.4 mm Hg PICO₂ led the U.S. Navy to propose an allowable level "in the neighborhood of 1% and preferably below 1% carbon dioxide for conditions of continuous prolonged exposure." More recent Navy standards for nuclear submarines (1975) offered three exposure-level limits [45]. The 1-hour emergency level was set at 2.5% FICO₂, the 24-hour continuous exposure level was 1% and that for a 90-day continuous exposure was 0.5%.

5.9 CONCLUSIONS & RECOMMENDATIONS

The literature on the acute and chronic effects of breathing increased fractions of carbon dioxide is extensive. At this writing, the PICO₂ limit established for the space suit for EVA workloads up to a metabolic rate of 1600 BTU/h is shown below [53]:

Continuous exposure - 7.76 mm Hg
Maximum for 1 hour - 22.75 mm Hg
Maximum (abort EVA) - 30.5 mm Hg

For EVA/EMU design considerations, two things must be considered. First, in the presence of an elevated FICO₂ there is evidence that oxygen consumption/uptake is increased during submaximal physical activity; and second, maximum oxygen uptake is reduced at maximum physical activity. The result is a decrease in physical work capacity. Therefore, in a simulated EVA environment (reduced pressure, hyperoxia, elevated physical activity, etc) we recommend that oxygen consumption/uptake studies be performed. The results would then form the design criteria recommendations for EMU design.

Although it is apparent that there are no major physiological effects at PICO₂'s up to 22.8 mm Hg (3%), there is no reason to deviate from the continuous exposure

limit established by Horrigan [53] in 1979 unless, it can be shown that to do so would be cost effective. He noted that, based on the data available at that time, the PICO_2 limit for space cabins had been set at 7.76 mm Hg (0.15 psia or 1.013 kN/m²). However, the PICO_2 lower limit at which there is probably no significant physiological, psychological, or adaptive change is considered to be about 3.8 mm Hg (0.5%).

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6 - PHYSIOLOGICAL EFFECTS OF REPETITIVE DECOMPRESSIONS & RECENT ADVANCES IN COMPRESSION SICKNESS RESEARCH

This section is in response to Section 2.6 in the SOW of the RFP, and was prepared by Dr. William J. Sears.

6.1 INTRODUCTION

Space Shuttle and Space Station operations planned for the 1990s and beyond are currently expected to involve repetitive decompressions of the extravehicular activity (EVA) crewmembers. It is prudent to consider the frequency of the decompressions and the proposed EVA work schedules in view of the potential long- or short-term health hazards that might result from repeated exposure to lower space-suit pressures. The many successful EVAs in earlier space flights reflect the considerable engineering and physiological design parameters that have provided a suitable environment for the EVA crewmember. Future missions will include a more varied group of participants than in past flights in regard to age, sex, and level of physical condition.

One of the concerns for future spaceflight activities is the intermediate and/or long term physiological or pathological complications which may develop from exposure to low barometric pressures, especially in those individuals who engage in EVA several times a week over long periods of time. More specifically, the possibility of decompression sickness (DCS) represents a major physiological implication both in spacecraft design and in mission planning. The potential for DCS is further affected by a variety of other microgravity and environmental effects that cause physiological change during the exposure to spaceflight conditions.

Although there are many physiological and engineering requirements to be considered during the construction and subsequent use of the Space Station, the objective of this section is to provide a review relevant to the specific physiological effects on crewmembers of repeated exposure to low pressures and the subsequent effect on EVA performance.

6.2 OVERVIEW OF THE SPACE ATMOSPHERIC SELECTION PROBLEM

Cabin atmospheres used in the NASA space program have been 100% oxygen at a pressure of 5 psia in Gemini and Apollo, 70% oxygen/30% nitrogen at 5 psia in Skylab, and air at sea level pressure in the Shuttle [1]. On the Apollo-Soyuz mission the Russian cabin atmosphere was 31% oxygen/69% nitrogen at a pressure of 10 psia [2]. Space suit atmospheres have been 100% oxygen at pressures of 3.5 to 4.3 psia [1,3]. Many conflicting factors entered into the selection of these atmospheres. A pure oxygen environment at low pressure allows considerable savings in vehicle weight and permits immediate transition of the crewmembers to suit pressure with minimum risk of DCS [4]. At low pressures, however, voice communication is more difficult and heat transfer efficiency is reduced [5]. The latter interferes with cooling of the electrical/electronic equipment. With enriched oxygen levels, the fire hazard is increased and there is an increased risk of aural and pulmonary atelectasis. These problems are avoided in the air atmosphere of the Shuttle, but a long prebreathing/staged decompression procedure is necessary before the crew can safely perform EVA at the present suit pressure of 4.3 psia [6].

6.3 REVIEW OF THE ETIOLOGY OF DECOMPRESSION SICKNESS

Notwithstanding the thousands of exposures of individuals to decreased atmospheric pressures over the last 50 years, the syndrome of DCS still remains poorly understood. However, there is general agreement on the following [7,8,9,10,11]:

- The condition is primarily the result of dissolved nitrogen coming out of solution at a rate faster than the body can eliminate it, resulting in bubble formation
- There appears to be a threshold altitude (or pressure differential) for bubble formation. This is likely a combined surface tension, diffusion and/or perfusion effect
- Once a bubble is formed from an inert gas, any other gas in the body's tissues or fluids may diffuse into the bubble resulting in rapid bubble growth.
- Different inert gases saturate and desaturate from different tissues at different rates
- There are wide differences between individuals in susceptibility to decompression sickness.

The manifestations of the disorder depend upon the site of bubble formation or

the site to which the bubble may be displaced. Symptoms range in severity from annoying pain in the extremities (bends) to serious neurological and cardiovascular problems that can lead to paralysis and death. Even if the individual escapes the more serious forms, he may become incapable of any useful activity; a serious circumstance indeed, if it occurs during spaceflight.

6.4 REVIEW OF PREVENTIVE MEASURES TO REDUCE DCS PROBLEMS

DCS is not normally a problem when the original partial pressure of the diluent gas (usually nitrogen) in the atmosphere, and thus in the tissues, does not exceed the final decompression pressure by more than a ratio of 1.5 to 1.6 [3]. A more conservative ratio is 1.4. The actual ratio varies from individual to individual and from tissue to tissue (e.g., muscle absorbs and expels nitrogen much more quickly than does fatty tissue). When changes in pressure will result in conditions exceeding these ratios, it is necessary to lower the pressure of dissolved nitrogen in the tissue prior to decompression to prevent DCS. Prebreathing 100% oxygen or equilibration with a lower partial pressure of nitrogen, as in staged decompression, have been effective in reducing the incidence of DCS. A higher suit pressure would also be effective, since the crewmember would not be required to exceed the critical nitrogen equilibration pressure ratio during EVA.

6.4.1 Preoxygenation

Because of the high rate of tissue utilization of oxygen, this gas does not contribute significantly to the formation or growth of a bubble. Therefore, an effective way to protect against DCS is to breathe 100% oxygen prior to decompression, thereby displacing nitrogen from the tissues; or at a minimum, to lower the concentration of nitrogen in the breathing gas, thus reducing the partial pressure of nitrogen in the tissue to a point at which the ratio is within the "safe" zone. This usually requires about 3 to 5 hours of preoxygenation depending upon the nitrogen pressure that exists within the body, (i.e., the lower the partial pressure of nitrogen within the tissues, the less time required for prebreathing at any given pressure level) [9].

6.4.2 Nitrogen Equilibration

In contrast to all preceding U.S. spacecraft, the Shuttle cabin has a "near earth" atmosphere of 14.7 psia (plus/minus 0.2 psia), with oxygen established at 3.2 psia (plus/minus 0.25 psia) and the balance nitrogen [1]. This means that the oxy-

gen ranges from 19.8% to 23.8% over the possible range of oxygen/cabin pressures. Consequently, DCS is not a possibility at lift-off, but at the point of preparation for EVA, it has been found that 3.5 to 4 hours of preoxygenation is required to give reasonable protection against DCS. This is considered a prohibitively long period of time to spend in a nonproductive mode. A search for an alternative protective scheme centered on the method of using nitrogen tissue/total pressure ratios to determine optimum combinations of pressures. Initially, an 11 to 12 psia cabin pressure equilibration was considered, but in order to achieve final nitrogen equilibration ratios comparable to those obtained with sea level prebreathing, suit pressure would have had to be raised to greater than 5 psia. Subsequent studies with the cabin pressure at 9.2 psia and 28% oxygen for 12 hours, followed by 30 to 45 minutes of 100% oxygen prebreathing before decompressing to 4.3 psia, showed a 6% incidence of DCS [12]. This was deemed a satisfactory risk in the event of a contingency EVA for the operational flight tests of the Shuttle, but the procedure was never put to test in space because of a potential hypoxia problem with the 9.2 psia equilibration procedure [3]. To minimize the fire hazard at 9.2 psia, a limitation of 30% had been placed on oxygen concentration [1,2]. When fluctuations of the gas pressure controller are considered, the worst-case oxygen level during the 12 hours equilibration period would approach the PO_2 found at 2,500 m (8,200 ft). While this is normally considered a safe level, it was not clear whether the pulmonary function and fluid redistribution changes that occur under microgravity conditions would intensify mild hypoxia and cause performance decrements. For later Shuttle flights, a compromise equilibration procedure was adopted. It involved 60 minutes of preoxygenation prior to reduction of the cabin pressure from 14.7 to 10.2 psia and 26.5% oxygen for 12 hours with 40 minutes of 100% oxygen prebreathing prior to EVA at 4.3 psia [1,3,13].

6.5 ANTICIPATED CREWMEMBER TASKING FOR SPACE STATION

The major influence upon Shuttle and Space Station pressure control, gas composition, and suit pressures will come from specific mission profiles, all of which involve EVA [14]. Specific tasks which may be conducted from space station are shown below [14,15]:

- Position, install, and remove construction equipment (EVA work station, restraints, lighting, jigs and fixtures, etc)
- Position construction material (position cargo pallets, move cargo items)
- Construction (fabricate structure elements, assemble structure modules,

deploy solar/reflector blankets, install components)

- Checkout and activation (use alignment and test instruments and fluid servicing equipment)
- Use the structure or payload for its intended purpose (replenish expendables, operate controls)
- Maintenance and repair (transfer fluids, repair damage, replace assemblies).

Preliminary Space Station mission profiles have generated a set of requirements that directly affect station and/or suit pressures [14,15,16]. These requirements include: 90 day crew stay times; 1 to 5 EVAs per week; resupply of consumables every 30 days - every 90 days maximum; located in Low Earth Orbit (LEO), with Orbit Transfer Vehicles for access to Geosynchronous Orbit (GEO) and; extended scope of EVA (fluid transfer, satellite reconnaissance and repair, and excursions to GEO). The space operations suit is currently foreseen as an evolution from the current Shuttle EMU suit; to an advanced Shuttle no-prebreathe 8.3 psia suit; to a non-venting EMU; to the Space Station EMU. Considerable effort is currently being placed on newer glove configuration and design to permit effective function at these higher pressures.

6.6 REVIEW OF REPETITIVE DECOMPRESSION SICKNESS RESEARCH

An extensive literature search on repetitive decompressions was conducted using the National Technical Information Service (NTIS), Aerospace, Medline, Excerpta Medica, Index Medicus and NASA Recon data base files as well as several classical texts and reviews. The literature on DCS is vast, amounting to several thousand references; and yet, the mechanism of clinical manifestations is far from being established. One of the most striking reasons for the paucity of current knowledge has been the absence of satisfactory experimental subjects other than large human groups. Small animals seem to be quite resistant to subatmospheric decompression sickness. Indeed, Fryer [9] "subjected rats to periods of one hour at 40,000 ft without apparent ill-effect" and reviewed other work where guinea pigs were exposed to the same conditions without provoking any reaction. He also noted that the American work with small animals during World War II was "generally unproductive of evidence for bubble formation under simple subatmospheric conditions except when very violent pressure changes were used, or animals were subjected to gross operative interference."

Until recently, most of the interest in repetitive decompression has involved exposure to hyperbaric conditions as in diving operations. Hills [10] reports that repetitive hyperbaric exposures appear to predispose the subject towards bends, although, "it is more difficult to isolate the effects of repeated decompression per se from those of repeated exposure upon the cumulative uptake of gases."

The pathophysiology involved in both altitude and diving DCS is probably the same qualitatively. However, the differences that exist relative to the absolute amount of nitrogen in various tissues at higher pressures, equilibration times at depth and the possibility of acclimatization to repetitive diving makes it extremely difficult to equate the two conditions in a linear fashion. As a result, emphasis has been placed on review of the literature on repeated exposure of humans to subatmospheric pressures using only selected animal and hyperbaric literature where necessary to fill information gaps.

6.6.1 Effects of Repeated Exposure to Subatmospheric Pressure on DCS

Symptomatology

The scientific literature as regards repeated exposure to subatmospheric pressures and the effect on an individual's tolerance to DCS is confounding. There is a wealth of anecdotal observation and comment, but very few studies designed to specifically address the question whether repeated exposure increases or decreases the subject's tolerance. Time between repeated exposures seems to be the most important single factor with altitude attained, exercise levels, physical condition, resolution of "silent" bubbles and other factors complicating the picture [9]. Another significant factor is that studies conducted before the 1970's used mainly subjective evidence of DCS during hypobaric chamber investigations (i.e., differences in subjective reporting of pain or other sensation and willingness on the investigator's/subject's part to tolerate higher levels of pain/risk from DCS). Comparing the results from these earlier studies to results from current studies which use the newer, more quantitative techniques of precordial Doppler ultrasonic monitoring and echocardiography and removal of the subject from experimentation with only Grade II pain is difficult.

6.6.2 Studies Indicating Increased Susceptibility to DCS

One of the early studies on repeated exposure to altitude was published by Rodbard in 1944 [17]. The results are shown in Table 6-1. It can be seen that

Table 6-1 Recurrence of Bends on Reascent (Rodbard, 1944)

Interval between ascents-minutes	No. subjects exposed	Proportion recurring-percent
0 to 20	5	100
21 to 60	52	50
61 to 120	52	52
121 to 180	13	38
181 to 1800	27	0
R88-6169-050		

there is almost a certainty of return of symptoms following a repeated decompression within 3 hours. The subjects in this study were exposed to 38,000 ft for 2 hours. Those reporting symptoms of DCS were brought to ground level for varying periods and then returned to 38,000 ft for 5 minutes to determine if symptoms recurred.

Motley et al (1945) in reviewing the incidence of DCS found that persons forced to descend because of bends from hypobaric chamber training flights to 30,000 and 38,000 ft for varying periods of time, developed over twice as many bends on the second flight as did those who developed bends, but did not need to descend [18]. One of the conclusions was that repeated flights increased susceptibility to bends. During the same year, hypobaric chamber technicians were exposed to 30,000 ft from 76 to 288 times per person with exposures as frequent as 2 per day [19]. Thirteen of the technicians (68%) became less resistant to bends leading also to the conclusion that an increased incidence of bends results from repeated exposure to reduced barometric pressures. Houston (1947) noted bends at altitudes as low as 17,000 ft and that daily ascents, together with the increasing "nervous tension," contributed considerably to the development of DCS [20]. Ferris and Engel (1951) concluded that reascent caused recurrence of DCS if carried out within a four to six hour period [21]. Hall et al (1952) exposed one subject to 43,000 ft for 0.5 h/day for 82 days and found that from the beyond the 75th exposure, the individual exhibited an increasing number and severity of "aeroembolism symptoms" [22]. He felt that "ageng" played little part in the increasing susceptibility to aeroembolism (DCS). In further experimentation, Hall (1955) exposed one subject to 142 repeated decom-

pressions to between 35,000 and 43,000 ft [23]. He found that the incidence and severity of symptoms of DCS rose and that the degree of descent necessary to ease symptoms simultaneously increased with repeated exposures. He concluded again that an increase in symptomatology occurs with repetitive decompressions. In that same year Vavala, in a review noted that the specific recurrence of bends upon reascent, after intervals of 4 to 6 hours, was strong evidence that bends is related to extravascular bubble formation, and that in successive exposures, there is a tendency for pain to recur in the same place [24]. Aver'yanov (1962) exposed dogs progressively to 1.4, 1.6, 1.8, 2.8 and finally 3.2 ATA for 4 hours and then decompressed the animals to ground level [25]. He concluded that repetitive decompressions from pressures where DCS symptoms are induced "does not increase resistance to DCS and may even decrease resistance." In another series of animal studies at high pressures, Griffiths et al (1971) concluded that DCS produced by repeated exposures has a shorter latency of onset than after single exposures [26]. He explained the findings on the basis of asymptomatic bubble formation after initial decompression. In other animal exposures to high pressures, Gait et al (1975) found that even after asymptomatic first dives, showers of bubbles were found which led to the appearance of arterial bubbles on subsequent decompression [27]. This group concluded that there is an increased susceptibility to bends after multiple decompressions. Hills noted earlier work showing that even while breathing pure oxygen, subjects became more susceptible to DCS with repetitive decompressions despite there being no opportunity for tissue take-up of more inert gas [10]. In an extensive review of DCS cases, Davis et al (1977) found that the incidence of DCS in inside hypobaric chamber observers undergoing two to four altitude exposures per week, accompanying students on altitude-chamber training flights, was three times greater than the incidence in the students [28]. In a more recent study to evaluate the period of excusal from flight following altitude chamber training, Olson et al (1979) found that previous exposure to U.S. Air Force aircrew refresher low pressure chamber training profile (35,000 ft) followed by a rapid decompression from 8,000 ft to 22,000 ft would predispose aircrews to bends in subsequent aerial flight, even with an 18-hour separation [29]. In a subsequent study, Adams and Olson (1982) found that by taking the rapid decompression prior to the high altitude training flight (rather than after), the chances for bends were lessened in a test flight conducted 18 hours later [30]. They suggested that taking the rapid decompression after the hypobaric chamber training flight would tend to stabilize bubbles for longer periods of time and subsequently give an increased incidence of bends. In a

recent review, Heimbach and Sheffield (1985) noted that a second exposure to an altitude greater than 5486 m (18,000 ft), following an exposure to such an altitude in the preceding three hours, will greatly increase the chance of DCS occurring, even if the first exposure was asymptomatic [11]. They further indicated that recurrence of symptoms is almost certain if the first exposure was symptomatic. Operational problems have also been noted by Marlowe [31] after several legs of cross country flights in unpressurized T-37 aircraft. These appear to be related to repeated exposure to altitudes between 20,000 and 25,000 ft. Eighteen cases of DCS were reported over a 10-year period. In chamber trials, Malconian et al (1986) exposed 23 subjects repeatedly from 15,000 to 29,000 ft with an incidence of DCS of 29.7% following a 30 to 60 min prebreathing period [32]. They found an increased incidence which appeared to be "related to degree of altitude and repeated exposure."

6.6.3 Studies Indicating No Change or Decreased Susceptibility to DCS

One of the first deliberate attempts to assess the effect of daily exposure to altitude was conducted by the RAF at Farnborough, England in 1941 [33]. A series of studies was conducted using different numbers of subjects experiencing exposures to different altitudes. In one case, two subjects were taken to 40,000 ft on six successive days with fewer symptoms noted during the last two days suggesting some adaptation to decompression. In a second study, one subject who was known to suffer from bends, was taken to altitudes above 30,000 ft for five successive days; given an interval of 6 days to rest, then given five more exposures; followed by a second interval of 7 days and three more exposures; and finally given an interval of 13 days with one more exposure. During this study the investigators found that daily exposure led to an "adaptation of a degree," but with the 13-day interval, there was increased symptomatology. The next study by this group exposed three subjects four times daily for 8 days to altitudes of 40,000 ft. After 32 decompressions the subjects showed no symptoms of fatigue or abnormality, and their blood sugar curves were normal. The few transient pains experienced early in the tests became less frequent later. None of the data suggested that there was any tendency for symptoms to recur on the day following their first occurrence. In another study of repeated exposure to altitude, Dill (1964) found postflight effects of mental depression, fatigue, irritability, etc, to occur in some individuals, but "no lasting harmful deterioration resulted from the altitude exposure [34]." Stewart et al (1942) observed the incidence of symptoms in 42 men during 14 consecutive daily ascents to 35,000 ft for 3 hours [35]. During the first four days the average inci-

dence of symptoms of all degrees of severity was 44%; in the middle four days it was 37%, while in the last four days it decreased to 28%. During the last four days this decrease was noted in moderate and severe cases as well as in mild cases. "Whether the decrease in incidence on repeated daily ascents was the result of acclimatization or a carry-over effect from the denitrogenation of the tissues on the preceding run was not decided." A further study was made by Stewart et al (1942) on the effects of reascents after periods spent at altitudes below those at which symptoms had disappeared or after periods at ground level [36]. On reascent from 15,000, 20,000 or 25,000 ft after intervals of 2 hours, pain always recurred in the same area and approximately the same altitude at which it had disappeared on initial descent. "With increased periods at ground level the altitude at which pain recurred became progressively higher and after a period of two to four hours there was no tendency for pain to recur in the same area any more frequently than intervals of 12 to 24 hours." Henry (1943) exposed 47 subjects four times to 38,000 ft with exercise [37]. About 7% of the runs were terminated because of "chokes or collapse." He found no statistical significance as regards the symptomatology during the repeated exposures. He suggested that it might be possible to screen for bends susceptibility, but indicated that even the most resistant individual will occasionally have symptoms. Smedal (1947, 1948) conducted two extremely relevant studies to examine the effects of repetitive decompressions to 20,000 ft. In the first study [38] he exposed 35 subjects twice daily for 30 minutes to hypobaric conditions for 28 consecutive days. The hypobaric chamber runs were conducted to 20,000 ft except on the 9th, 15th and 22nd day when control runs were made to 10,000 ft; and on the 29th day when a control run was made to 6,000 ft. In all runs, the subjects were told that they were being exposed to 20,000 ft. The subjects used masks and diluter demand oxygen regulators during all exposures. Exercise was completed every 5 minutes for the 30 minutes altitude exposure. The subjects noted mild joint distress, paresthesias, headache, fatigue and changes in appetite, but no differences in the percent of incidences of complaints were found in the separate altitude runs. An increase in fatigue was the only significant finding at 20,000 ft. Smedal concluded that repetitive decompressions to 20,000 ft did not result in an increase in severity of DCS symptoms. In a subsequent study, Smedal (1948) exposed 25 subjects to altitudes of either 5,000 ft or 20,000 ft for 30 minutes with exercise every 5 minutes [39]. The subjects were told that all runs were to 20,000 ft for a total of 240 man-exposures to 5,000 ft and 1039 man-exposures to 20,000 ft. There were very few complaints of specific symptoms on either the 5,000 ft or 20,000 ft exposures.

Again, no differences were found in the percent incidence of complaints at either 5,000 ft or 20,000 ft. Smedal confirmed his earlier findings that repetitive decompressions to 20,000 ft showed no further increase in symptoms other than more fatigue. These findings are echoed in comments by Adler [7] who notes that, "most persons demonstrate no definite change in susceptibility to dysbarism on repeated exposures," and Fryer [9] who notes, "there is no clear cut answer to whether changes in DCS symptomatology occur as a result of repetitive decompressions." Burkhardt et al (1947) repeatedly exposed seven individuals to 38,000 ft and found that only one of the seven became more susceptible with time [40]. He noted that rest periods of several days or more seemed to have "a beneficial effect in preserving tolerance to bends." In animal studies to establish decompression schedules for use in behavioral work, Thomas et al (1973) repeatedly exposed rats to three air and helium schedules and found them to be "relatively free from barotrauma and decompression problems [41]." Petrukhin et al (1975) exposed both humans and dogs to repetitive decompressions between 36,091 ft and 39,372 ft with "no persistent pathological changes found in the animal or human [42]." The humans in these studies were exposed to altitude for 2, 3, 20 or 24 hours after denitrogenation of differing duration for a total of 133 hypobaric chamber exposures. The dogs were exposed to altitudes of 39,372 ft for up to 2.5 hours without denitrogenation for a total of 88 exposures. Histological and histochemical examinations of organs and tissues of three dogs were performed. In an extremely relevant study, Barer et al (1979) exposed 200 subjects, after denitrogenation periods of 15 to 60 minutes, from 760 mm Hg to 10 to 20 mm Hg (using spacesuits at pressures ranging from 160 to 310 mm Hg) for exposures of from 1 to 10 hours [43]. Exercise loads ranged from 150 to 400 kcal/h. They found that at suit pressures of 270 to 310 mm Hg and without denitrogenation, there were "no decompression sickness problems." At suit pressures of 160 to 230 mm Hg with 15 to 60 minutes denitrogenation, they found "bends of different severity." The lower frequency of cases of DCS in suited subjects as compared to the literature on unsuited subjects was attributed to "suit pressures and kinematics of movements"; therefore, during EVA, astronauts may, in fact, not experience bends as readily as might be expected from unsuited hypobaric chamber bends studies.

In more recent studies, Waligora et al (1984) conducted three study series to examine the effects of repetitive decompressions on humans [44]. In Series 1 (36 subjects), the individuals were exposed to a 12- to 18-hour stay at 10.2 psi breath-

ing 26.5% oxygen, balance nitrogen, mixture with 40 to 90 minutes prebreathe before decompression to 4.3 psi. Eleven subjects were also exposed to 3.5 hours of pre-breathing 100% oxygen at 14.7 psi prior to decompression to 4.3 psi with an exercise workload of 200 kcal/h imposed on the experimental subjects during the two conditions. In Series 2, the subjects were exposed to the 10.2 psi protocol and a 3.5-hour prebreathe period before decompression to 4.3 psi with exercise over the 4 hour exposure period. In series 3, a 6-hour exercise period with 17 hours between 4.3 psi exposures, was imposed on the subjects with return to either 14.7 psi or 10.2 psi. The authors concluded that the repeated simulated EVA exposures after only 17 hours did not increase symptoms of DCS or bubble incidence. In a summary article, the same authors concluded that either the 4-hour prebreathe at 14.7 psi or the 12-hour stage decompression to 10.2 psi using 27% oxygen could be used to support EVA activity on consecutive days [45]. Further work in the same laboratory has shown that the highest incidence of bubbles, and the only incidence of DCS symptoms occurred on the first EVA of the first day using staged decompression at 10.2 psi [46]. Incidence of bubbles were reduced during the 2nd and 3rd days of the three day studies. In a subsequent review by the primary authors, they suggested that a reasonable schedule would be three EVAs per week with the possibility of EVA for 40 or more hour per week [47]. Dixon et al (1986) reported on a study that exposed 30 subjects, in groups of three, to three consecutive daily EVA simulations at 7.8 psia for six continuous hours with exercise [48]. Although 73.3% of the subjects had intravenous bubbling for at least one day of the 3-day exposure, successive exposures did not result in more severe bubbling nor in the occurrence of DCS. The only progressive bubbling change found was a significant reduction in the time-of-onset of bubbling, suggesting "that either bubbles or bubble precursors remained between exposures."

6.6.4 Conclusions

The studies cited supporting both an increase susceptibility to DCS with repetitive exposures to subatmospheric pressures, and a decrease or no change in susceptibility, span a 40-year plus period. Although there are more references which support the finding of an increased susceptibility, no significance is attached. One would have to compare each study on a case-by-case basis. However, two conclusions emerge from the data:

- EVA at reduced atmospheric pressures with no more than 4-6 hours between evolutions is not recommended

and

- EVAs using NASA's present approach to denitrogenation (prebreathing and staged decompression) is adjusted safe as long as there is at least an 18-hour period between evolutions.

6.7 METABOLIC & OTHER FACTORS COMPLICATING THE EFFECTS OF REPETITIVE DECOMPRESSIONS DURING PROLONGED SPACE FLIGHT

6.7.1 General

There is an absolute paucity of data as regards metabolic changes that occur during decompression to subatmospheric pressures. Most of the knowledge has been derived from examination of fatalities which, unfortunately, is not very relevant to the topic at hand; nor has the investigation of fatalities been very revealing. There are several physiological adaptations to microgravity, however, that may complicate earlier findings on the effects of repetitive decompressions. A summary of these space related issues has recently been prepared by Hunt and Buckley [49]. The cardiopulmonary issues include, orthostatic intolerance, decreased exercise capacity, cephalad fluid shift, increased peripheral vascular compliance, altered cardiac dynamics/electromechanics and altered pulmonary function. Muscular/musculovascular issues include: decreased strength, decreased muscular endurance, decreased muscle mass and altered neuromuscular function. Bone and mineral issues include; bone demineralization and altered calcium balance. Blood issues include; altered hematological, biochemical and immunological functions. Special senses issues include; vision, hearing and kinesthesia/proprioception/spatial discrimination. Space adaptation issues include Space Adaptation Syndrome and treatment regimens. The relationship between these microgravity related issues and non-microgravity issues such as decompression sickness, radiation and illness or injury have not been defined, and there is question whether the combined effects can realistically be determined in a one-g environment. On the other hand, it has been adequately demonstrated that the crewmember has the capacity to live, work and perform various activities for long periods (in one case up to a year) in a microgravity environment [3,50].

6.7.2 Literature Review

In 1941 Evelyn [51] examined the respiratory, circulatory and renal systems of 40 subjects following repeated exposures to altitude and noted only a change in blood

cholesterol, and concluded that there were "no findings of general importance." Patel and Gowdey (1963) exposed rats to oxygen pressures of 60 psi for short intervals and found only minimal lung pathology and no changes in the blood picture [52]. Cooke and Bancroft (1966) decompressed dogs from 200 or 250 mm Hg to 1 mm Hg within one second for periods from 55 to 240 seconds before recompression to ground level [53]. All exposures were regarded as dangerous with potential for cardiac damage, but they concluded that survival was more dependent on damage to vital structures other than the heart.

West and Parker (1973) reviewed earlier data to determine the extent to which DCS might be predicted on the basis of physical condition [54]. They found a positive relationship between increasing age and weight and increased potential for DCS, but the correlation was low. They concluded that to reduce the risk of DCS; an individual should avoid strenuous exercise after a pressure change; avoid pressure changes of 6 to 7 psi and; keep temperatures at the low end of the comfort zone. The role of exercise coupled with an increased blood carbon dioxide content has been known to increase DCS symptoms since the early work of Henry in 1945 [55]. He exposed young men a total of 390 times to 38,000 ft. The results led to his concluding that: "pain occurs in unexercised limbs, but is much more common and more severe in exercised limbs; onset time, incidence and severity of pain are systematically related to total work (in foot pounds). There is an indication that the occurrence of mild pain is differentially affected by small amounts of work, but not further increased at the highest work level studied. Muscle strain, mechanical tension and amount of joint movement do not determine the occurrence or severity of pain and; the results support a theory that increased local carbon dioxide production is principally responsible for the effects of exercise on the occurrence and severity of altitude pain." Maio et al (1950) however, in a careful study of energy expenditure at altitude, found no correlation between grade of bends symptoms and rate of energy utilization [56]. These authors speculated that the increase in bends with exercise was more the result of "the rate of flexion of major joints together with the absence of adequate denitrogenation." Philp and Gowdey (1962) found that moderate forced exercise in rats will precipitate DCS and make it more severe [57].

Syftestad and Boelkins (1976) found no significant change in femur wet weight, density, ash weight, length, or mineral content after exposure of 1, 3, 5, or 7 times to either 1 ATA helium/oxygen for 12.5 hours or to 5 ATA helium/oxygen for 4

hours and a 1.5-hour decompression [58]. Kupper (1976) exposed squirrel monkeys repeatedly to both hypobaric and hyperbaric profiles and noted no clinical, radiologic, or postmortem evidence of osteonecrosis during either the 6 month exposure period or the following 13-month observation period [59]. Hallenbeck (1978) "could not confirm or deny the occurrence of chronic progressive encephalomyelopathy" following an extensive review of the data on repetitive decompressions [60]. Osteonecrosis occurring during hyperbaric exposure is relatively well established, but there is little solid evidence of osteonecrosis occurring during repetitive decompressions to subatmospheric pressures [9,10,61].

In other decompression studies, Sedov et al (1980) showed no increase in DCS symptomatology when breathing oxygen contaminated with human waste gaseous products [62]. Heyder and Tappan (1981) exposed divers to two series of dives to 6.7 ATA for 45 to 50 minutes in a dry chamber; four dives at 3-day intervals or five dives performed daily [63]. They found no diuresis or changes in glomerular filtration rate, but did find "an increasing extent of metabolic changes during the first few dives," but were not specific as to what the changes were. They found adaptation (decrease or lack of symptomatology) to repeated dives after 2 to 3 dives, particularly when performed at 3-day intervals. Convertino et al (1984) measured maximal oxygen uptake, ventilation, heat rate, systolic and diastolic pressures, plasma volume and body composition during bed rest studies to determine exercise capacity following Shuttle flights [64]. They concluded that two weeks of minimum activity are adequate for complete recovery from simulated weightlessness and that repeated exposure can be safely tolerated. Other authors have investigated blood changes following repetitive decompressions and found the blood white cell count (WBC), activated partial thromboplastin, blood urea nitrogen, inorganic phosphate, potassium and osmolality were "slightly, but significantly increased while a slight decrease was found in uric acid [65]." Assessing whether or not these data are of practical importance is difficult, since all values measured were within normal ranges, and the tests were conducted in a one-g environment.

Energy expenditure during various space activities have been measured at around 150 to 240 kcal/h [3,4,44]. Most of the recent studies to establish safe prebreathing or stage decompression levels are using exercises that simulate energy expenditures of around 150 kcal/h [66]. The desirability of providing arms-in capability in space suits has recently been addressed [67]. This capability would

likely reduce the need for reentering the cabin for sustenance, etc, and thereby eliminate the need to go through repetitive decompressions on more than a daily basis. Although the literature on long term physiological/metabolic effects of repeated exposure to subatmospheric pressures does not, by itself, support the need for suit redesign, a conservative approach would consider this option favorably.

6.8 OPTIMAL COUNTERMEASURES AGAINST THE POTENTIAL EFFECTS OF DECOMPRESSION SICKNESS

The literature abounds with information on nitrogen washout by breathing pure oxygen for varying periods of time. The exact time required depends upon altitude attained, duration of exposure and many other individual and environmental factors [7-11]. Although the prebreathe option has proven effective against DCS over the years, the procedure does require that the crewmember be placed in a generally unproductive mode during denitrogenation and other protective options have been sought to negate this loss of productivity.

Cheetham (1947) apparently was the first to report that DCS, upon exposure to 37,000 ft, was less prevalent among men dwelling at moderately high altitudes as compared with low elevations [68]. He considered the extremely low susceptibility to DCS among dwellers at an elevation of 4,700 ft to be "owing to not only a smaller pressure gradient, but also a smaller volume of nitrogen available for release into the circulation." His idea was later confirmed by Balke's [69] observations at higher elevations during which a mobile altitude chamber was used in repeated tests with seven men. Balke's records show, for example, that brief residence near the peak of Mt. Evans (14,000 ft) was sufficient to lessen the incidence of DCS during exposure to 38,000 ft. Indeed, after 3 to 4 days living at 14,000 ft, grade III bends pains were not observed at 38,000 ft in the hypobaric chamber trials. Furthermore, on subsequent ascent to altitudes between 42,000 ft and 56,000 ft for a total time of 30 to 40 minutes, there were no symptoms of DCS. Balke also noted that residents of Morococha in the Andes never suffered from decompression sickness when exercising for 30 minutes at 38,000 ft; whereas "newcomers to this village at 14,900 ft were susceptible only during the first day and thereafter were completely protected just as those born and dwelling at this elevation."

Allen et al (1969) studied the effects of decompressions from 14.5 to 9.7 psia; from 9.7 to 5 psia; from 14.5 to 5 psia; and from 9.7 to 3.5 psia [70]. He found

that decompression from 14.5 to 9.7 psia in a 33% oxygen/67% nitrogen atmosphere can be tolerated without producing bends in working men. After remaining 4 hours at 9.7 psia, these authors noted that "it appears safe to decompress to 5 psia in a 70% oxygen, 30% nitrogen atmosphere, but not to 3.5 psia." As an interesting side note, the rationale for using enriched oxygen at 33% was that "the combustibility parameter for 33% oxygen at 9.7 psia is similar to air at one atmosphere." In another study, Allen and Beard (1969) exposed subjects, with only 2 hours of denitrogenation at ground level, to 5 psia breathing either 70% oxygen (balance nitrogen) or 100% oxygen with subsequent ascent to 3.5 psia breathing 100% oxygen [71]. Exercise consisted of in-place marking time for 30 steps in 15 seconds, repeated every 15 minutes, while exposed to the 5 psia atmospheres (simulated intra-vehicular activity), and every 5 minutes at 3.5 psia (simulated extravehicular activity). Of the total 102 manflights, 45 individuals had symptoms of DCS and "80% of the grade 1 bends increased in severity while the subjects remained at altitude and continued with exercise." This study offers evidence that if the crewmember experiences bends pain during EVA, the chances are good that the pain will tend to become more severe until he returns to higher pressure.

Earlier work by Balke (1954) and the study by Maio et al (1970) point to evidence that the picture is not as clear as many might think regarding exercise and DCS [56,72]. Balke investigated the effect of preoxygenation coupled with exercise prior to ascent to 38,000 ft and found that "mild and severe exercise on the treadmill, with the subject breathing ambient air, did not increase the susceptibility for decompression sickness during subsequent ascents to high altitude." He found that nitrogen elimination was dramatically increased with exercise as compared with rest while prebreathing pure oxygen and stated that "the tolerance for decompression sickness is not necessarily correlated with the amount of nitrogen removed." He further suggested that "from a practical point of view, preoxygenation during light exercise of a general type would be advisable on occasions when the most effective protection against high altitude pains is required within a limited time." It was noted earlier that Maio et al [56] could not correlate energy expenditure and incidence of bends at altitude. Chernyakov et al (1975) conducted six 3-day experiments simulating repeated EVA activities with intensive work at 32,810 ft breathing oxygen from a helmet assembly and at 131,240 ft in a pressure suit pressurized to 200 mm Hg [73]. During the 3-day study, the subjects made seven 3- to 4-hour ascents. They found that with "prolonged exposure to atmospheric pressures of 430

mm Hg and 100% oxygen, or 40% oxygen and 60% nitrogen mixtures, there were no symptoms of decompression sickness." They concluded that DCS can be prevented by denitrogenation at intermediate altitudes.

Over the past six years there has been a series of reviews [74-78], experiments [12,13,79-86], and theoretical models' [87-89] that have attempted to define the limits for bubble formation, protective procedures and equipment that would allow the crewman to function satisfactorily in space. Flugel et al (1984) reviewed the problems associated with prebreathe operations and proposed a zero-prebreathe suit to eliminate the need for prebreathing or staged decompression prior to EVA [74]. Krutz et al (1985) reviewed earlier studies to determine minimum pressures for a zero-prebreathe suit and suggested that pressures around 9.5 psia would be required for "bends free" operation [75]. Greider (1984) presented an extremely lucid and provocative argument relative to cabin pressures, percent oxygen and suit pressure for repeated EVA's [76]. He proposed a 7.4 psia (18,000 ft) cabin pressure using 40% oxygen/60% nitrogen as an intermediate stage before exposure to 4.3 psia, 100% oxygen suit pressure. This recommendation was based on both physiological as well as logistics considerations. Waligora (1984) presented considerations for various cabin and suit pressures as well as maximum oxygen concentrations and constraints for repeated EVA's [77]. Horrigan and Waligora (1980) reviewed the historical aspects of the protective schemes used for protection of spacecrews against DCS and proposed an alternate use of a 9 psi stage decompression for Shuttle [78]. Bassett (1984) was able to show the related effects of flying after diving [79]. His experimental findings indicated that when using the no-decompression limits for diving, the diver can expect to get bends and/or higher grades of bubbling above flight altitudes of 8,500 ft. Horrigan et al (1984) found a high level of bubbling during a 6 hour exposure at 4.3 psi pressures, but did note a decrease in gas emboli during the last three hours of exposure [80]. Krutz et al (1985) exposed 57 subjects to altitudes ranging from 16,000 ft to 30,000 ft while breathing a slightly hyperoxic gas mixture [81]. Exercise levels were equivalent to EVA and the exposure period was 8 hours. He found that as altitude increases, the number of false positives (bubbling without bends) decreases such that at 30,000 ft, "there are essentially no false positives." He noted that "the association of bubbles and bends does not exist at pressures less than or equal to 7.8 psia." An inference was made that bubbles do not reach a sufficient size to produce DCS symptoms above 9 psia.

Dixon and Krutz (1985) subsequently exposed both male and female exercising subjects to 9.5 psia for 6 hours while breathing 40% oxygen and 60% nitrogen and found no bends resulting from the exposure with only grade 1 and 2 bubbles in four of the male subjects [82]. They concluded that 9.5 psia will protect the astronaut from severe bubbling and development of bends symptoms. Horrigan et al (1986) conducted a study that used a 10.2 psia staged decompression for 24 hours combined with a 6 psia suit pressure for protection against DCS [83]. They concluded that this procedure would have a "very low probability of eliciting intravascular bubbles or symptoms of DCS." In a separate paper, Waligora et al (1986) exposed 19 males and 19 females to decompression from 14.7 to 4.3 psia after 6 hours prebreathe [84]. Also, 15 males and 14 females were equilibrated at 10.2 psia and then decompressed to 6 psia. In both studies, the subjects worked for 6 hours at simulated EVA workloads before repressurization. There was no statistical difference found in the incidence of symptoms or venous gas emboli between males and females. In another experiment designed to evaluate female susceptibility to DCS, Dixon and Krutz (1986) exposed 30 females to three consecutive EVA simulations at 7.8 psia for a continuous exposure of 6 hours while breathing 50% oxygen and 50% nitrogen with simulated EVA exercise workloads [85]. They found that 43.3% of the female subjects had intravenous bubbling at least one of the three days of exposure. DCS symptoms were experienced by 16.7% of the subjects; and two of these were delayed. These authors noted that "female subjects appear to suffer more delayed DCS symptoms than males, but do not tend to bubble as frequently." Smead et al (1986) also used male and female subjects to evaluate DCS and venous gas emboli at 8.3 psia [86]. The subjects were exposed to 8.3 psia for 6 hours with simulated EVA equivalent workloads and while breathing a 50% oxygen/50% nitrogen mixture. Limb bends incidence was 3.2% with 25.8% of the subjects demonstrating significant intravascular bubbling. The authors concluded that 8.3 psia was inadequate to "totally preclude the risk of decompression sickness."

Other "protective" measures have been suggested that include; use of aspirin to reduce potential platelet clumping and microemboli; prehydration of the individual prior to exposure, and use of several other pharmacologic agents to treat severe reactions resulting from DCS [9]. Definitive studies have not been conducted to determine the potential benefits of these measures.

Other authors have taken a more theoretical approach to resolving the issue of DCS. Vann and Torre-Bueno (1984) have developed a critical volume hypothesis for selection of Space Station pressures so that flightcrews may decompress immediately from sea level to station pressure without prebreathing [87]. Hills (1985) using physiological principles, has concluded that an astronaut, breathing a mixture of 30% oxygen in nitrogen for 4 to 5 hours in a spacecraft at 11.9 psia can transfer to a space station filled with the same mixture at 8.7 psia and, after an additional 4 to 5 hours, go EVA in a 4.3 psia suit at any time without oxygen prebreathing [88]. He states, "The incidence of DCS is estimated to be less than 0.5% using suit pressures of 4.3 psia, and the incidence could be reduced to zero if suit pressures were increased to 6.5 psia." Gernhardt (1986) has developed a theoretical model derived from physical laws which predicts that bubble growth is pronounced at 3 psi and 4.3 psi with some growth at 8 psi and with no bubble growth at 9 psi [89].

6.9 RECOMMENDATIONS FOR FURTHER STUDIES

The ultimate aim of studies on DCS should surely be to prevent the crewmember from being exposed to the more serious complications of the disorder. The goal should be an atmospheric combination of cabin or suit pressures that does not cause DCS, preferably without prolonged periods of prebreathing and using simple operational procedures. The final decision, however, must be tempered with consideration for other factors, which include the flammability hazard, waste heat removal, structural weight, equipment complexity, regard for logistics and consumables, individual work/performance and mission requirements, as well as potential for long-term health effects. It becomes evident, after reviewing the massive data base on DCS and state-of-the-art equipment design, that some compromises will be necessary until such time that the individual can be placed in a one-atmosphere micro-environment which allows him to function at least as well as wearing the current pressure suit design during EVA.

From the literature review on repetitive decompressions, it does not appear likely that repeated EVAs will present any short or long term health hazards of consequence, especially in view of the current concept of using stage decompression at 10.2 psi and a 4.3 psi suit. This holds true for the future anticipated use of higher pressure suits in the range of 8 psia and above. It also appears, from the many empirical studies that have been conducted relevant to staged decompression and prebreathing as well as the theoretical modelling approaches for selection of ap-

appropriate cabin and suit pressures, that investigators have a reasonable "handle" on the effects of DCS and the capability to extrapolate between the use of nitrogen ion and prebreathing techniques. There are, however, several questions that beg for further study, some of which can only realistically be resolved in a microgravity environment.

It is recommended that the following studies be conducted to:

- Determine the rate of elimination of nitrogen by prebreathing pure oxygen in microgravity conditions
- Measure the effect of prebreathing a mixture of oxygen and carbon dioxide on the incidence of DCS
- Determine if there are significant differences in flame spread rates between 30% and 35% oxygen to not allow compromise for the mild hypoxia in a "worst case" staged cabin pressurization scheme
- Resolve the question of whether the combined effects of long term microgravity induced physiological changes influence the potential for DCS
- Determine if there are any "real" benefits that can be derived from pharmacological or physiological intervention, e.g., aspirin, hydration
- Unravel the physiological/physical/metabolic mechanisms that form the basis for exercise causing an increase in the incidence of DCS at altitude
- Determine the relative effects of different forms of exercise, e.g., isotonic versus isometric in the etiology of DCS
- Measure differences in the incidence of bubbling and DCS in suited and unsuited subjects at the same pressure level
- Develop techniques to screen out individuals susceptible to DCS
- Develop standardized metabolic studies for all future research on DCS
- Determine if the drugs used to reduce the effects of the Space Adaptation Syndrome have any effect on the incidence of DCS
- Resolve the logistics, consumables, environmental conditioning of equipment, etc, for providing stage decompression pressures up to 9 psia.

The conservative approach to the prevention of DCS that is currently being taken by NASA and other laboratories has proven effective from both a health and functional standpoint. There have been many experimental studies and literally thousands of hypobaric chamber training flights that have exposed individuals to repetitive decompressions to much lower pressures than previously experienced

during Shuttle EVA or proposed for Space Station EVA. Long term sequelae to subatmospheric DCS are extremely rare, particularly in comparison to the long-term effects of work in compressed air.

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7 - THERMAL BALANCE

This section is in response to Section 2.7 in the SOW of the RFP, and was prepared by Dr. Conrad Monson.

7.1 INTRODUCTION

The purpose of this section is to determine both the quantity and quality of information related to thermal balance and EVA work, identify and describe thermal balance limits applicable to EVA work, and identify and describe research needed to develop more effective limits for EVA work based on thermal balance considerations.

In the era of Space Station, as during the Gemini, Apollo and Shuttle programs, thermal balance considerations will limit the extent and duration of potential EVAs. Unlike the EVAs of past U.S. space programs, EVA during the operation of Space Station will be relatively long (8 hours/day), will be conducted over an extended period of time (90 days), and will be costly. Because of the extended nature of Space Station EVA, an understanding of thermal balance during EVA work will be important in establishing physiological limits that allow maximum human productivity while minimizing cost.

7.2 THERMAL REGULATION IN GENERAL & UNDER EVA CONDITIONS

In humans, thermoregulation can be modelled as a proportional controller. The primary control elements, thermoregulatory neurons, reside in the hypothalamus whereas sensory and effector elements (thermosensitive, motor and other effector neurons) are located throughout the body. In addition to hypothalamic and thermosensitive neurons, the thermoregulatory system is also comprised of neurons and effectors for generating, conserving, or dissipating body heat. These effectors include muscles, blood vessels, sweat glands and elements of the respiratory system. Activation of these effectors will generate, conserve or dissipate heat. Heat is generated as a result of muscular activity including shivering. Heat is conserved by constriction of blood vessels in the skin and periphery of the body. Finally, heat is dissipated by vasodilation of skin and peripheral blood vessels, evaporation of sweat

produced by sweat glands and evaporation of mucous and saliva in the respiratory tract.

In addition to these physiological mechanisms of thermoregulation, there are also behavioral mechanisms for regulating body heat. Such very familiar activities as putting on or removing clothing, moving into shady or sunny environments and locating close to or far from sources of heat are examples of thermoregulatory behavior routinely practiced by humans. In controlling body temperature, these behaviors are at least as important as the physiological mechanisms just described.

Although thermoregulatory processes in mammals are influenced by changes in gravity [1], data from space flights supports the idea that the operation of the thermoregulatory system in microgravity is not different from the operation of the thermoregulatory system in the one-g environment of Earth. However, during routine EVA, there are constraints on thermoregulation, constraints that do not exist in most environments on Earth. For example, the current design of space suits minimizes the transfer of radiant heat energy into or out of the suit. As a result, thermal radiation from space is not normally a source of heat gain to an EVA astronaut. Likewise, thermal radiation from the suit to space is not a significant source of heat loss [2]. In a space suit, the main source of heat is metabolic heat, and under most EVA work conditions, heat dissipation is the major thermoregulatory challenge to the body. The use of a space suit constrains thermoregulation in other ways as well. For example, astronauts wearing suits cannot put on or remove excess clothing. Also, sweating has to be avoided to avoid unfavorable increases in the water content of the space suit environment. In general, space suit limitations for providing suit heating, for storing and dissipating excess heat or for removing toxic substances limit the range and variety of mechanisms available for human thermoregulation during EVA. In developing thermal balance limits to EVA work, these suit constraints need to be carefully considered.

7.3 SCOPE OF STUDY & STUDY LIMITATIONS

The scope of this section is limited by several factors. First, after conducting a literature search, it was readily apparent that there has been little space- or Earth-based research on the physiological limits to EVA work, much less on the impact of thermal balance considerations on those limits. In contrast, there are a large number of papers reporting the results of basic and applied research on

thermal balance during work in the one-g Earth environment. Because of the amount of this research, only a relatively small number of papers reporting Earth-based research were reviewed for impact on physiological limits to EVA work.

Subsections of this report describe the results of selected research relevant to thermal balance during actual EVAs as well as thermal balance during work on Earth. This literature review provides the basis for the recommended EVA work limits. Recommended work limits are followed by a concluding section describing research needed to further delineate useful EVA work limits based on thermal balance considerations. In reviewing the literature and in recommending limits and further research, an integrated approach has been emphasized. That is, a range of physiological and logistics factors have been considered for impact on EVA work limitations based on thermal balance considerations.

To investigate thermal balance limits to EVA work, five databases in the "DIALOG" system were searched using an IBM personal computer and a modem connected to the central database library. These databases included NASA RECON, NTIS (National Technical Information Service), MEDLINE (Index Medicus bibliographic entries), EXCERPTA MEDICA and DTIC (Defense Technical Information Service). The data items in these databases consisted of government reports, basic and applied research reports and review articles. Reports and articles to be examined were selected by the "DIALOG" computer from this list of total data items. The selection process involved the identification of common key words in the reports and articles. Key words were chosen so that the data items selected for review were related to thermal balance and EVA work capacity or to thermal balance and work in general. Key words were combined by the computer so that a reasonable number of data items related to thermal balance and work could be selected for review. The results of the literature search are discussed in the following subsections.

7.4 EFFECT OF CHANGES IN AMBIENT TEMPERATURE ON EVA WORK PERFORMANCE

Over the years, there have been numerous studies of the effect of ambient temperature on work performance. Unfortunately, in spite of this research effort, it has proven difficult to generalize regarding ambient temperature effects on work performance. For example, after an extensive review of research in the area of work performance, Kobrick and Fine [3] concluded that "generalizations about the

effects of heat or cold on performance are almost impossible to make on the basis of available data." They did find that some performance tasks, such as vigilance tasks, are impaired when ambient temperature is between 29° and 32°C . The performance of some cognitive tasks was impaired at temperatures above 38°C , whereas performance of other tasks improved at temperatures above this level. In summary, the effect of ambient heat on performance was equivocal; that is, for similar exposure conditions, there were decrements, improvements or no change in psychomotor performance, reaction time and various other types of tasks.

In reviewing the effects of cold ambient temperatures on work performance, Kobrick and Fine [3] found that there has been much less research in this area than on the effects of heat on work performance. The main effect of cold on work performance was in a loss of the manipulative abilities of the hands below an ambient temperature of 16°C . Also psychomotor tasks tended to be significantly effected at temperatures below -7°C whereas there was no effect on visual reaction time during cold exposure. Kobrick and Fine concluded that "no conclusions can be drawn about the effects of cold on categories of tasks other than manual dexterity."

7.4.1 Effect of Increased Core Temperature

The effect of increased core temperature on performance is not clear cut. In a study of simulated flying tasks, pilots were exposed for 50 minutes to two levels of heat, 43°C and 60°C [4]. During 60°C exposure, deep body temperature increased 0.35°C and skin temperature increased 1.0°C . At these temperatures, performance of some of the simulated flight tasks was impaired relative to the performance of these tasks at 27°C . However, there was no clear relationship between the performance decrements and the physiological changes. All the physiological changes were within tolerable limits. These investigators concluded that complex tasks (i.e., those that required a high degree of mental alertness, muscular coordination and function) were more susceptible to degradation under hot ambient temperatures than were simple tasks such as meter monitoring.

In other investigations of the effects of increased body temperature on work performance, researchers [5] found that whereas brief periods of increased core temperature (increases of approximately 2°C) resulted in increased subject irritability, brief increases in core temperature also resulted in increased speed of performance on calculation and verbal reasoning tests. Memory registration was

unaffected by the increased body temperature. In an Eastern European study [6], work capacity as measured by endurance time, strength, etc, first increased, then decreased during the development of hyperthermia. In conditioned athletes, this increase in work capacity was consistently 8-12% above normal levels when body temperature was 38.7-39.1°C; in unconditioned subjects, the effect was more inconsistent and less pronounced.

The results of research on the effects of increased core temperatures point out the difficulty in attempting to develop physiological limits to heat exposure based on the physiological effects of increased ambient or core temperatures. That is, as reviewed above, performance of some tasks improves when core temperature is elevated by a brief period of heat exposure; in contrast, the performance of other tasks is degraded. Of course, if the heat exposure is sufficiently prolonged and intense, performance of all types of tasks will eventually be compromised.

7.4.2 Effect of Lowered Core Temperature

The effect of lowered core temperature on work performance has not been studied as extensively as has the performance effect of raised core temperatures. Nevertheless, degraded performance of some tasks has been attributed to lowered core temperatures. For example, when core temperature drops by about 2°C, there is a significant, detrimental effect on cognitive performance [5]. Also, memory registration is adversely affected when core temperature drops below 36.7°C [7]. The effect on memory registration is especially pronounced at 35°C, a core temperature routinely reached in healthy, cold-water swimmers such as North Sea divers. (The cold-induced effect on memory registration was thought to be due to cold-induced slowing of synaptic transmission across neural junctions.)

In another study of work performance in subjects with lowered body temperatures, performance actually improved when body temperature decreased by as much as 1°C [8]. As indicated by a reduced sweat rate, the "thermoregulatory load" was reduced by the lowered body temperature. Under these conditions, work rate increased. Thus, whereas significantly lowered core temperatures (less than about 35°C) and skin temperatures can result in reduced work performance due to hypothermia and the loss of manipulative capability of the hands, slightly lowered core temperatures (decreases of about 1°C) can improve work performance.

7.4.3 Effect of Skin Temperature

The effect of skin temperature on work performance may be at least as important as the effect of core temperature; under certain conditions, skin temperature may be more important in determining work performance than is core temperature. For example, in a study of simulated flying that included controlling a throttle and control stick, Gibson et al. [9] found that differences in task performance could be produced by heating or cooling the skin at a constant core temperature. Above a critical core temperature, skin temperature was a more important determinant of performance than was body (core) temperature. Furthermore, heating was more detrimental to task performance than was cooling.

In another study [10], performance of a pursuit-rotor task was measured when skin and core temperatures were increasing. Performance was found to be more closely related to mean skin temperature and subjective comfort than to deep body temperature. Furthermore, the effects may be due to the changes in temperature rather than to the absolute temperature levels. Finally, hypocapnia that developed during heating and the state of arousal of the test subjects were also thought to be factors in the performance decrements.

7.5 EFFECT OF MULTIPLE ENVIRONMENTAL STRESSORS ON EVA WORK PERFORMANCE

As reviewed above, changes in ambient temperature, body temperature and skin temperature can have both positive and negative effects on work performance. Changes in ambient temperature in combination with other environmental stressors such as hypoxia and humidity, can result in even greater performance decrements compared to the performance changes associated with a single stressor. For example, in a study of work performance in humans at various altitudes, Lahir et al. [11] found that exposure to hot, humid environments at sea level is as incapacitating as is exposure to hypoxia without heat or humidity stressors. These investigators speculated that the combined detrimental effects of heat; humidity and hypoxia, a combination of stressors not found in nature but definitely possible in a space suit, would be additive.

On the other hand, exposure to single or multiple adverse environmental conditions may not be detrimental to performance. Instead, exposure to arousing environmental stressors may actually improve, rather than degrade, work

performance. In a review of the effects of environmental stressors on work performance, Poulton [12] challenged the validity of the widely held rule that adverse environmental conditions such as heat, noise and vibration degrade performance. As indicated by performance measurements rather than subjective assessments, a person may improve his performance when suffering physical discomfort. For example, Poulton reviewed the results of several experiments that showed performance of speed and vigilance tasks improved when ambient temperature was above the upper end of the comfort zone (i.e., at temperatures above 26°C). In other experiments, people with core temperatures above 38.5°C improved their performance even though they felt uncomfortably hot. Psychologists have explained the improvement in performance as due to a heat-induced, heightened state of arousal.

7.6 OTHER FACTORS AFFECTING WORK PERFORMANCE

In addition to those factors discussed above, there are other factors that should be considered in developing work limits to EVA based on thermal balance considerations. For example, there are significant differences in the thermoregulatory processes of men and women. Relative to men, women in a warm environment tend to store greater amounts of heat due to decreased sensitivity and delayed onset of sweating [13]. As a result, the body temperatures of women show a greater increase in hot environments than do the body temperatures of men. Furthermore, the thermoregulatory response of women in thermally stressful environments is complicated by body temperature changes associated with ovulation. The differences in the thermoregulatory responses of men and women need to be carefully considered in designing EVA work limits. Finally, other factors should also be carefully studied including the effect of hot or cold acclimatization, effect of hypoxia, and general physical condition of the astronauts who will be suffering from the deconditioning effects of chronic weightlessness.

7.7 EFFECT OF THERMAL HEATING & COOLING DEVICES ON EVA WORK PERFORMANCE

The design of space suits, life support systems and cooling garments limits the duration and intensity of EVA work. Since the first space suits were developed, the suit equipment for heating or cooling an astronaut has evolved from simple systems using air to the more complicated liquid-cooled garments (LCG). This evolution has been documented for both the American and Soviet space programs, and requirements for cooling during Shuttle and Space Station EVAs have been described [14,15,16].

In an early review, Nunneley [17] compared the cooling capabilities of LCGs with the capabilities of air-cooled garments. After examining rectal temperature and sweat rate changes, she concluded that LCGs were much more effective at reducing heat stress than were air-cooled garments. Furthermore, LCGs were found to be more comfortable and to provide greater cooling capacity than did air-cooled garments.

In spite of the capabilities for effective cooling, there are problems inherent in the design of LCGs, problems that limit the effectiveness of LCGs during EVA work. For example, compared to a simple air-cooled system, LCGs are more cumbersome and immobilizing. Furthermore, wearing a pressurized suit with a LCG was found to increase the metabolic cost of performing tasks by 400-600 kcal/h, a cost that is 2-4 times greater than in an unpressurized suit [17]. As pressurized suit and cooling system designs improve, the metabolic cost of task performance due to suit wearing should decrease. However, it is doubtful that the cost will ever reach zero.

Control of suit temperature is another problem with space suits, regardless of the type of cooling system employed. Several investigators have studied methods for controlling water temperature in liquid-cooled garments [17,18]. During manual control of LCG temperature, there is a lag between the adjustment of water temperature in response to perceived discomfort and a change in core temperature to a more comfortable level. As a result, there tends to be a chronic under- or over-cooling with manually controlled cooling systems. Although automatically controlled systems correct some of the problems associated with manually controlled LCGs, automatic controllers typically rely on cumbersome physiological measurements such as rectal temperature in the control circuit. In 1970, Chambers [19] studied LCGs and methods for controlling their cooling capacities. He reviewed the adequacy of gas ventilated garments to handle the thermal loads experienced during Apollo EVAs. He also described three types of automatic controllers; a fluidic controller that maintains constant skin temperature, a metabolic controller based on changes in oxygen consumption and a differential controller that responds to the difference between actual and desired skin temperatures.

In another study of automatic control systems for LCGs, Kuznetz [18] used NASA's "41-node Metabolic Man Computer Program" to calculate comfortable water inlet temperatures for an automatically-controlled LCG under various conditions of

thermal loading. He studied the effectiveness of this automatic system in three test subjects. The results of several measurements such as metabolic rates, heat removal rates, and comfort index showed the automatic system maintained body heat storage, sweating and overall comfort to an acceptable level during exercise.

Other investigators [20,21] have also assessed the cooling effectiveness of LCGs based on physiological measurements and subject assessments. Control based on either changes in oxygen consumption or skin temperature resulted in effective and accurate adjustments to suit temperature to match the cooling needs of working test subjects. Furthermore, after working, properly cooled subjects felt less fatigued than did poorly-cooled subjects. Poorly-cooled, suited subjects experienced eye irritation, visor fogging, discomfort from sweating without evaporation, dehydration, exhaustion and eventual collapse due to excessive body heat storage in the suit.

Over the past several years, two investigators [22,25] have studied the effects of head and torso cooling (in contrast to whole body cooling) on overall thermal comfort and balance. Some investigators thought that head cooling should be effective at reducing the overall body heat load because: (1) the head has a rich scalp vasculature that remains dilated even at low temperatures, (2) there is the possibility of countercurrent exchange between blood vessels entering and exiting the head, and (3) the head has been found to be important in determining overall thermal comfort. Thus, although the head represents only 10% of the body surface, the head was thought to exert a significant, measurable effect on overall thermal comfort and performance in thermally-stressed individuals.

Experiments have substantiated the idea that head cooling is effective at reducing performance decrements associated with higher than normal body temperature. In a variety of studies, head cooling in thermally-stressed individuals resulted in little to significant changes in task performance. For example, Nunneley et al [23,24] demonstrated that head and torso cooling can reduce the adverse performance effects of heat exposure during simulated flight as well as during other types of tasks. Head cooling diminished forehead sweating and thus reduced the danger of "blepharospasms" that can occur when sweat enters the eyes. Head cooling was also found to reduce thermal discomfort in individuals with core temperatures driven to high levels by heat from liquid-filled garments or from heat generated during work [Nunneley, 24,25]. Finally, because of the head vasculature

and relative cold-insensitivity of the scalp, the head can be cooled to as low as 5°C without discomfort [24] whereas exposing the whole body to 5°C would be extremely uncomfortable.

In planning for Space Station EVAs, the effectiveness of head and torso cooling, as well as heating, should be carefully considered.

In addition to the need for body cooling inside space suits, there will also likely be the need for body warming. Body warming would be required whenever the rate of metabolic heat production was less than the rate of space suit heat removal. As previously discussed, if astronauts had to work while cold, performance and safety could be adversely effected.

Although technological advances will undoubtedly improve the thermal capabilities of space suits, it is likely that there will always be a limit to the heat removal and generation capabilities of space suits. Liquid-cooled garments seem to be the best current solution to thermal balance problems experienced by suited astronauts performing EVA work. However, future research may develop alternative designs that are at least as effective as LCGs, but less immobilizing. In a recent study, Pimental et al [26] found a newly developed air cooled vest to be effective at increasing endurance times and reducing thermal strain in working subjects wearing a set of chemical, biological and radiation protective clothing. Further research will be required to determine the best solution to Space Station astronauts thermal balance problems during EVA.

7.8 LIMITS

Accurate physiological limits to EVA work based on thermal balance considerations can only be determined after EVA tasks have been defined. The tasks for Space Station EVA should be carefully studied to determine the metabolic cost, heat generated, psychological and motor skills required for task performance. Tasks that require heavy work and result in the output of a high level of metabolic heat will likely increase core temperature. These tasks should not be executed in conjunction with tasks that require a high level of cognitive skills. As discussed previously, increases in core temperature of as little as 0.35°C can impair the ability to perform complex tasks. Even though core temperature increases of up to 2°C can increase the performance of some cognitive tasks, the attendant increase in irritability and

discomfort would make such an increase in body temperature unacceptable. Then small increases in body temperature of up to 1°C may be acceptable and even beneficial for some types of EVA tasks whereas increases of 2°C or more should be avoided.

Likewise, a 2°C drop of core temperature should be avoided during EVA. As reviewed previously, core temperature decreases of 2°C can adversely effect cognitive performance whereas a 1°C decrease can improve work performance. A 1°C decrease in core temperature should be acceptable as a limit for core temperature decreases during EVA.

To maintain a core temperature at 1°C above or below normal will not only require the selection of appropriate work tasks but will also require the regulation of the ambient temperature in the suit. Based on the literature reviewed, to avoid vigilance task impairment, ambient temperature should not exceed 38°C . To prevent the loss of manipulative ability in the hands, ambient temperature should be maintained above 16°C .

7.9 RESEARCH RECOMMENDATIONS

As previously discussed, without a greater research effort, accurate limits to EVA work based on thermal balance considerations cannot be made. Limits need to be based not just on one-g research on the physiology of work, but research also needs to be tailored to the EVA work environment. Some of the issues that should be addressed in a tailored research effort include:

- The metabolic requirements of each EVA task. Once the requirements are determined, EVA work could be scheduled so that tasks most likely to cause increases in core temperature are not executed in conjunction with tasks requiring high levels of cognitive skills. Inherent in this research effort would be the identification of the cognitive and muscular work requirements for EVA tasks
- The effect of high and low ambient temperatures on EVA work requirements with a particular emphasis on the effect of cold on gloved-hand performance. Another objective of this research effort would be to document the effect of ambient temperature on core temperature during the execution of EVA tasks

- The identification of other physiologic stressors associated with EVA besides thermal stressors. The impact of these stressors on thermal balance during EVA work should be assessed
- Determination of those tasks (if any) more suited to males versus those more suited to females
- Determination of the type of suit thermal control system (e.g., air cooled, liquid cooled, torso cooling, helmet cooling, etc) most effective for thermal control during EVA work.

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8 - URINE COLLECTION

This section is in response to Section 2.3 in the SOW of the RFP, and was prepared by Donald H. Peterson and Dr. Paul A. Furr.

8.1 INTRODUCTION

During EVA, the capability for collecting and storing urine will be important to the comfort and performance of the EVA crewmember. The proposed duration (up to 8 hours) of Space Station EVA may necessitate space suit urine collection and storage. In addition to minimizing discomfort, there should be no contamination of other suit subsystems such as the air supply or the drinking water supply. Current Space Station plans include a space suit with a 1000 ml capacity for urine collection.

A literature search did not reveal any pertinent studies relative to physiological factors concerning urinating in space suits during exposure to the microgravity environment. It soon became apparent in conversations with NASA JSC engineers and medical personnel that even though urine collection devices were used by EVA astronauts during training exercises as well as in some EVA missions in space, no formal reports or records existed. Engineering design data on both male and female urine collection devices (UCD) is well known to NASA, and will not be discussed here.

8.2 METHODOLOGY

In order to collect data from EVA astronauts concerning their experience with UCDs, Grumman in cooperation with the Medical Operations Branch, Medical Sciences Division, JSC prepared a comprehensive questionnaire which was sent to the Shuttle EVA astronauts (Appendix C). In it, their familiarization with the UCD both during training as well as during actual EVA missions was sought. Of 16 astronauts who performed Shuttle EVAs, data was collected from nine.

8.3 RESULTS

8.3.1 Familiarization During Training

All nine astronauts responding indicated that they had donned/worn a UCD for familiarization. During familiarization/training periods, one astronaut wore the UCD only once or twice. The longest period was 2 hours. Five wore the UCD less than five times, and the average longest period of wear was 5.9 hours (range: 2 to 8.5). Three astronauts wore the UCD more than five times, with the longest period for each being 8 hours. The astronaut who wore the UCD only once or twice stated that familiarization was adequate, and there was no need for further experience with the device in the training environment.

Seven of the nine astronauts responding used, or attempted to use, the UCD as part of familiarization. However, one stated a concern about leakage due to the UCD's reputation for failure. The two who did not use the UCD stated that it was not necessary for familiarization. One of these astronauts stated: "I didn't need to, and didn't care to. If I'd needed it, I would have used it." When asked if the UCD was used, was the performance of the device satisfactory, five astronauts responded in the affirmative; but, one stated that the device leaked due to poor fit. He was using a prototype UCD. One astronaut who used the UCD responded that the performance was unsatisfactory due to "failure," but did not specify the nature of the failure. One astronaut indicated that the UCD was used as part of familiarization, but did not respond to the question, was performance satisfactory.

8.3.2 UCD Experience During Actual EVA

The nine astronauts reporting performed 13 EVAs. One reported a single EVA lasting 30 hours, 30 minutes. He may have meant 3 hours, 30 minutes. For the 12 remaining EVAs, the average duration was 5.27 hours with a range of 3 hours to 7 hours. This does not necessarily represent the total time in the suit, but is considered to be the time the astronaut was on suit power. One astronaut, in fact, specified an additional 3 hours prebreathe time (not included in the calculation of the above average time). Another specified an additional 1.5 hours pre- and post-suit time not included in his statement of EVA duration time.

All of the astronauts completing the questionnaire stated that they wore the UCD during EVA missions. Two used it. In one case the EVA lasted 3.5 hours,

and in the other, 7 hours. One astronaut reported satisfactory performance with the UCD, one reported unsatisfactory results. It leaked. For the remaining EVAs, the astronauts responded that there was no "physiological need" to use the UCD.

Several anecdotal comments were provided by the astronauts:

"With proper quality control the UCD works fine...and can't think of a better way to go."

"I wore and used a UCD during prelaunch/launch. Using it while lying on one's back is difficult. It worked fine."

"I did wear a UCD for launch and used it in the clean room just outside the vehicle. It leaked and had to be removed, and resulted in a urine spill in my flight coveralls. Other than very minor discomfort, there was no problem."

The above two comments were made by astronauts who did not use the UCD during an EVA.

"Now that we leak test them, the current UCD is OK by me. I can't imagine a much better solution for 0-G that I'd care to use, e.g., diaper (no thanks), catheter (no thanks)."

8.4 DISCUSSION

Though our study contains data from only nine astronauts out of 16 who performed Shuttle EVAs, it is considered to be an adequate sample. The type of UCD used primarily by the Shuttle astronauts consisted of a condom and urine collection bag. One female astronaut wore the Disposable Absorption Collection Truck (DACT) during an EVA, but did not use it; and although at least one male astronaut expressed a distaste about wearing a "diaper," several females who have worn the DACT for familiarization and confidence trials at home report that it is a satisfactory device - not uncomfortable even after use. In fact served as padding to protect the wearer from contact with "hard points" inside the pressure suit. No spills were experienced with the DACT, or while removing it after use; whereas, spills/leaks have been reported by male astronauts using the condom/collection bag UCD.

Though there may be some esthetic distaste about "wearing a diaper" (the DACT), the females who wore it report that it kept them dry and comfortable. One female astronaut when asked about other concepts of UCDs for females reported the "female anatomical devices" proposed were not satisfactory, because they did not fit correctly, leaked and/or were uncomfortable. Psychological factors associated with urination cannot be ignored. However, based upon the proven performance of the DACT and the relatively large number of failures of the UCD, perhaps male astronauts should reconsider the use of the DACT device/concept. (The bases of their rejection of the DACT appears to be based solely upon its "diaper" connotation, and does not recognize its actual performance.)

8.5 CONCLUSIONS & RECOMMENDATIONS

The male UCD exhibits a real risk of leaking. The "female anatomical device" UCD which funnels urine into a collection bag does not seem to be too popular. Any "free urine" collection system (i.e., condom or peritoneal cup) not only poses a collection problem (i.e., spills, discomfort), but a disposal problem as well. Whereas, the DACT UCD virtually eliminates the spill problem, it does pose a psychological problem (i.e., "diaper") for some astronauts and would require more storage space and a greater weight penalty.

We therefore recommend that:

- New technology be identified and pursued as much as possible
- A trade study be undertaken to assess the pros and cons of the "free urine" collection systems versus the pros and cons of the DACT system.

APPENDIX A
LITERATURE SEARCH DATA

APPENDIX A

LITERATURE SEARCH DATA

OXYGEN LEVELS

1. Search Terms:

Work capacity
Hyperoxia
High altitude
Cosmonauts
Hyperbaric chamber
Pilot

Hypoxia
Work
Astronauts
Hypobaric atmosphere
Physical exercise
Aerospace medicine

2. Total records captured: 138,460

3. Number of records reviewed: 162

CARBON DIOXIDE LEVELS

1. Search terms:

Carbon dioxide
Human performance
Life support system
Human
Physical exercise
Work capacity
Limit
Hypercapnia
(Biological and Medical Sciences)

Extravehicular activity
Human factors engineering
CO₂
Exercise physiology
Work
Space
Exertion
(Medicine and Biology)

2. Total records captured: 722,047

3. Number of records reviewed: 211

FOOD AND WATER REQUIREMENTS

1. Search terms:

Space flight feeding
Food intake
Pressure suits
Extravehicular activity
Space flight
Water deprivation

Space suits
Nutritional requirements
Water balance
Water loss
Space stations
Diet

2. Total records captured: 132,514

3. Number of records reviewed: 214

REPEATED DECOMPRESSIONS

1. Search terms:

Scheduling
Human tolerances
Decompression repeated
Aerospace medicine
Chronic
Repeat

Decompression sickness
Pressure reduction
Extravehicular activity
Altitude sickness
Acute
Multiple

2. Total records captured: 562,692

3. Number of records reviewed: 202

THERMAL BALANCE

1. Search terms:

Temperature regulation
 Work
 Work capacity
 Control
 Temperature effect
 Physical exercise
 Exercise physiology
 EVA
 Thermal comfort
 Cold
 Heat acclimatization
 Hyperoxia
 Life support systems
 Stress physiology
 Human factors engineering

Thermoregulation
 Human
 Temperature
 Exercise
 Temperature control
 Human performance
 Extravehicular activity
 Space
 Heat
 Cold acclimatization
 Temperature balance
 Hypoxia
 Physiological effect
 Human pathology
 Clinical medicine

2. Total records captured: 600,847

3. Number of records reviewed: 192

HAND MOBILITY, TACTILITY, FATIGUE

1. Search terms:

Hand
 Range motion
 Work capacity
 Dexterity
 Tactile
 Strength
 Perception of comfort

Hands
 Temperature and effect
 Glove
 Tactility
 Work performance
 Fatigue
 Sensory

Temperature
 Wetness
 Human engineering
 Electroencephalography
 Literately
 Comfort
 Touch
 Sensory perception
 Fatigue (biology)

Humidity
 Human factor
 Space suits
 Motor cortex
 Drug effects
 Pharmacodynamics
 Tactile discrimination
 Physical work

Also searched "pschinfo" file

2. Total records captured: 692,184

3. Number of records reviewed: 1189

OPTIMUM WORK

1. Search terms:

Work
 Orbital workers
 Workload
 Space flight

Physical exercise
 Physical fitness
 Work rest cycle
 Airplane pilot

2. Total records captured: 204,912

3. Number of records reviewed: 259

APPENDIX B

HUMAN STUDIES

HUMAN STUDIES*

Literature ReviewLow-Level CO₂

A detailed literature review was conducted to assess the responses of humans who have been chronically exposed to low levels of CO₂. Some reports of high-level CO₂ exposures were included within the review. A reviewer categorized all of the reported responses into "change" or "no-change." "No change" was judged to be the case by one of the following criteria:

- a. The author reported a low level of statistical significance $p < .05$, by comparison with a control.
- b. The reviewer judged, from the variability of the measured response to the CO₂ exposure, that the response would have occurred during a non-CO₂ exposure. Such judgment was required when multiple t-tests were used to test statistical significance rather than the appropriate analysis-of-variance.

"Change" was judged to be the case when:

- a. The author reported a high level of statistical significance, $p < 0.05$, by comparison with a control
- b. The reviewer judged that the response resulted from an exposure to CO₂.

General Results of Literature Review

The review yielded 22 separate exposures which embodied data collected from 212 adult men (Table 1). Nine studies were performed in the laboratory and 12 were performed during submarine patrols. The mean inspired partial pressure of carbon dioxide, (PICO₂) was 10 torr (S.D. 7 torr) and the mean duration was 40 days (S.D. 23 days). The ranges of exposure were 3.8 to 30 torr, PICO₂, during 1 to 90 days of exposure. There were no reports of health impairments attributed to carbon dioxide.

Primary Responses, Pulmonary Function

The observed rise of the alveolar ventilation in one study raised the possibility that low-level CO₂ might stimulate ventilation (Table 2a).

*Reference: From NSMRL Report No. 973, "Position Paper: the Toxic Effects of Chronic Exposure to Low Levels of Carbon Dioxide," 19 January 1982.

Table 1a Literature Review, Conditions of the Exposure

<u>Reference</u>	<u>PI,CO2 Torr</u>	<u>Exposure Time, Days</u>	<u>Number of Men</u>	<u>Laboratory Study</u>	<u>Submarine Patrol Study</u>
A	5	90	4	✓	
B	7.6	63	12		✓
C	30	14	4	✓	
D	11.4	42	23	✓	
E	23	5	5	✓	
F	6.1	20	-		✓
F	6.8	20	10		✓
G	22.8	1	1	✓	
H	3.8	13	6	✓	
I	5.3	52 [~]	15		✓
J	3.8	40	9	✓	
J	11.4	12	4	✓	
K	6	64	15		✓
L	6.1	56	10		✓
L	7.6	56	-		
M	7.6	56	31		✓
N	6.5	52	20		✓
O	14	30	6	✓	
P	7.6	40	15		✓
Q	9.1	46	10		✓
R	7.6	54	5		✓
S	<u>?</u>	<u>60</u>	<u>7</u>	<u>-</u>	<u>✓</u>
Mean	10	40			
S.D.	7	23			
Total			212	9	12

R88-6169-053

A summary of the pulmonary function changes is given in Table 2a. The respiratory frequency did "not change" while the tidal volume was often found to "change." The physiological dead space "changed" and the respiratory minute volume often changed. The alveolar partial pressure of carbon dioxide ($PACO_2$) always changed in the few studies reported. There were "no changes" of the vital capacity, inspiratory reserve volume, or expiratory reserve volume. The ventilatory responses to increments of inhaled CO_2 often showed "changes." The data may be presumed to represent changes of the alveolar ventilation by enhancement of the tidal volume.

Primary Responses: Blood Gases & Acid-Base

The arterial partial pressure of carbon dioxide (PCO_2) always "changed" in the few studies reported (Table 2b).

As shown in Table 2b, the mixed venous PCO_2 tended to "change" in blood and frozen specimens. The venous pH tended to "change" as did the arterial pH and the

Table 2a Summary of Changes, Pulmonary Function

<u>Measurements</u>	<u>"No Change"</u>	<u>"Change"</u>	<u>$PiCO_2$</u> Mean & S.D.	<u>References</u>
respiratory minute volume	2	5	9.3 ± 3.3	48, 52, 58
tidal volume	2	4	8.6 ± 3.6	48, 52, 58, 61
respiratory frequency	6	1	8.7 ± 3.3	48, 52, 58, 61, 62
vital capacity	3		8.4 ± 2.7	48, 58
expiratory reserve volume	1			48
inspiratory reserve volume	1			48
physiological dead space		6	8.1 ± 3.3	48, 52, 58, 61
\dot{V}_A		1	11.4	48
$PACO_2$		3	9.7 ± 5.3	45, 48, 56, 61
Ventilatory response to CO_2	1	3	9.1 ± 2.7	48, 58

R88-6169-054

capillary pH. The content of bicarbonate tended to "change" in the venous plasma, venous blood, arterial plasma, and arterial blood.

The urinary excretion of ammonium probably "changed" during the exposures. Less dramatic were the "possible changes" of urinary pH, CO₂ content of the urine, and gastric acidity. There was some evidence that "no changes" occurred in the

Table 2b Summary of Changes, Blood Gases & Acid Base

Measurements	"No Change"	"Change"	PICO ₂ Mean & S.D.	References
PaO ₂		2		57,62
PaCO ₂ , blood or plasma		4	9.8±3.6	50,57,61,62
Pc,CO ₂	1			56
P _v , CO ₂ blood		1	6	57
P _v , CO ₂ frozen plasma	1	2	7.6	41,43,59
PCO ₂ , frozen RBCs		1		43
[HCO ₃ ⁻] a, plasma		2	9.5±2.7	50,62
[HCO ₃ ⁻] v, blood		3	6.7±0.8	43,57,59
[HCO ₃ ⁻] a, blood		1		57
[HCO ₃ ⁻] a, RBC		1		50
[HCO ₃ ⁻] v, plasma	2	3	8.6±4.0	41,43,49,61
[HCO ₃ ⁻] excretion, urine	2	1	7.2±5.89	54,56,61
[CO ₂] urine		1	11.4	50
[CO ₂] saliva	1		9.1	63
pHc, blood		1		56
pHa, blood		3	9.2±4.2	50,57,61,62
pHa, plasma		1		50,57,61,62
pHv, plasma	2	3	7.6±2.4	41,43,49,59
pH urine	1	1	10.8±4.5	59,60
gastric acidity		1	7.6	64
urinary net acid	2	1	7.7±5.5	56,61
titratable acidity	2	2	9.5±6.4	41,61
24 hour urinary "acid-base balance"	1		5.0	42
urinary ammonium excretion		3	6.7±4.9	55,56,61

R88-6169-055

Table 2c Summary of Changes, Electrolytes

Measurements	"No Change"	"Change"	References
Na ⁺ balance	1	1	50,56
Na ⁺ excretion	1	4	50,56,57,59
[Na ⁺] plasma	4	4	41,43,44,50,56, 57,59,61
[Na ⁺] RBC		3	43,50,59
[Na ⁺] saliva	1		63
K ⁺ balance	2		50,56
K ⁺ excretion, urine	4	2	44,50,56,57,59
K ⁺ excretion, feces	2		56
[K ⁺] plasma	3	4	41,43,50,57,59,61
[K ⁺] RBC		1	43,50,59
[K ⁺] saliva	1		63
Cl ⁻ excretion, urine	3	1	50,56,59,61
Cl ⁻ excretion, feces	1		56
[Cl ⁻] plasma	4	2	41,43,50,56,57,59
[Cl ⁻] saliva	1		63
[Cl ⁻] RBC	1	2	43,50,59
Ca ²⁺ balance	1	1	56
Ca ²⁺ excretion, urine	2	7	
Ca ²⁺ excretion, feces	1	1	56

R88-6169-056

urinary excretion of net acid, titratable acidity of urine, salivary content of CO_2 , and urinary excretion of bicarbonate.

Secondary Responses: Electrolytes

The secondary responses to low-level CO_2 were represented by measurements of a wide array of bodily functions (Table 2c). Table 2c summarizes the fluid balance of humans in low-level CO_2 . The electrolyte metabolism was examined out of concern for possible responses to alterations of the body's acid-base balance. The few studies suggested that the sodium balance could "change." The urinary excretion, plasma concentration, and red blood cell concentration of sodium tended to "change." Although the plasma and erythrocyte concentration of potassium probably "change," there was the possibility that "no changes" occurred in potassium's balance, urinary

Table 2c Summary of Changes, Electrolytes (contd)

<u>Measurements</u>	<u>"No Change"</u>	<u>"Change"</u>	<u>References</u>
[Ca^{2+}] plasma	3	5	41,49,55,56,59, 61
[Ca^{2+}] RBC		1	59
[Ca^{2+}] saliva	1		63
Mg^{2+} balance	2		56
Mg^{2+} excretion, urine	1	4	44,55,56,59
Mg^{2+} excretion, feces	2		56
[Mg^{2+}]plasma	3	1	55,56,59
Zn^{2+} excretion, urine		1	44
Phosphorus balance	2		56
PO_4^{-3} excretion, urine	4	5	44,49,50,55,56, 57,59
PO_4^{-3} excretion, feces	2		56
[PO_4^{-3}]plasma	6	2	41,49,55,56,59, 61
PO_4^{-3} saliva		1	63

R88-6169-057

excretion, salivary concentration, and fecal excretion. The chloride concentration of the erythrocyte possibly "changed," but neither its plasma concentration nor its urinary excretion seemed altered. There was possibly "no change" of chloride's salivary concentration or fecal excretion. Sparse data suggested that the calcium balance "changed" and that the magnesium balance did "not change." Aside from "no change" of the salivary concentration, and fecal excretion of calcium, the plasma concentration, urinary excretion, erythrocyte concentration, and fecal excretion of calcium tended to "change." "No changes" tended to occur in magnesium's plasma concentration and fecal excretion. The urinary excretion of magnesium and phosphorus probably "changed." The balance of phosphorus tended to "not change." The phosphorus concentration of plasma and excretion in feces tended to "not change," while its salivary concentration tended to "change." The urinary excretion of zinc possibly "changed."

Secondary Effects: Water Balance

There was strong evidence that the 24-hour urinary volume did "not change" (Table 2d).

Table 2d Summary of Changes, Water Balance

<u>Measurements</u>	<u>"No Change"</u>	<u>"Change"</u>	<u>References</u>
water balance	1		56
24-hour urine volume	6	1	55,56,59,61
fecal excretion water	2		56
% water blood	1		49
% H ₂ O, plasma	2	1	45, 49, 57
hematocrit	1	2	60,61
erythrocyte count	1	2	45,60,61
[Hb]	1	1	45,60
salivary flow	1		63
creatinine excretion, urine	2		56
creatinine clearance	1		56

R88-6169-058

There was probably "no change" of the plasma water content or the body weight. Despite possible "changes" of the hematocrit and erythrocyte concentration, sparse evidence suggested "no change" of the water balance, fecal excretion of water, water content of the blood, hemoglobin concentration, flow of saliva, creatinine excretion, and creatinine clearance.

Secondary Effects: Bone

The urinary excretion of hydroxy-proline, plasma concentration of calcitonin, and plasma concentration of parathormone tended to "not change." Decrements of vitamin D concentration in plasma have been measured (Table 2e).

Secondary Effects: Metabolism

The metabolism tended to "not change" as evidenced by a few studies showing "no change" of the body temperature, daily intake of food, fecal wet-weight, fecal dry-weight, fecal nitrogen excretion, and nitrogen balance (Table 2f).

Possible "changes" were noted in the respiratory exchange ratio, oxygen uptake, ventilatory excretion of carbon dioxide, and the urinary excretion of nitrogen. Possibilities of "no change" were also found for the plasma concentration of cortisone, the reticulocyte count, and the white blood cell count. Possible "changes" occurred in the polymorphonuclear and eosinophile counts.

Secondary Effects: Cardiovascular & CNS

The blood pressure, heart rate, and psychomotor task performance tended to "no change." Hand steadiness and the electroencephalogram possibly "changed" (Table 2g).

Table 2e Summary of Changes, Bone

<u>Measurements</u>	<u>"No Change"</u>	<u>"Change"</u>	<u>References</u>
hydroxyproline excretion, urine	2	1	56, 59
[Vitamin D], plasma		2	56, 65
[Calcitonin] plasma	1		59
[Parathormone] plasma	1		62
R88-6169-059			

Table 2f Summary of Changes, Metabolism

<u>Measurements</u>	<u>"No Change"</u>	<u>"Change"</u>	<u>References</u>
body temperature	1		46
body weight	2	1	46,56
N ₂ balance	1		50
daily food intake	1		56
fecal N ₂ excretion	1		50
fecal wet-weight	1		56
fecal dry-weight	1		56
N ₂ excretion, urine		1	50
respiratory exchange ratio	1	1	50,61
$\dot{V}O_2$	1	1	48,61
$\dot{V}CO_2$	1	1	48,61
ventilatory excretion CO ₂		1	45
[Cortisol] plasma	1		62
Reticulocyte count	2		45,60
white blood cell count	1		45
[EOS 's]		1	45
[PMN's]		1	45

R88-6169-060

Table 2g Summary of Changes, Cardiovascular & CNS

<u>Measurements</u>	<u>"No Change"</u>	<u>"Change"</u>	<u>References</u>
test of performance	2		45,61
blood pressure	1		46
heart rate	1		46
hand steadiness		1	51
EEG		1	51
EEG, sleep		1	45

R88-6169-061

Discussion

A major problem with the conduct of this review was the variety of standards-of-reference for judging significant changes of the measurements. Therefore, the reviewer classified the results into measurements which did or did not change from various reference measurements. The reviewed data collectively represented a continual exposure of men to 1.32% CO₂ (PICO₂ = 10 torr) for 40 days.

A preponderance of the changes were in the functionally related responses of the ventilation, blood gases, and acid-base status of the subjects. Equations predicted that the alveolar ventilation (therefore, the respiratory minute volume) will rise when the inspired levels of CO₂ rise for a given state of metabolic activity:

$$\dot{V}_A = \frac{\dot{V}_{O_2} \times k}{PACO_2 - PICO_2}$$

The data from this review showed that the respiratory minute volume changed in response to inspired fraction of carbon dioxide (FICO₂)'s between 0.5 and 2% (3.8 to 15 torr), implicating a more responsive respiratory center than previously thought.

The stability of the body water balance, nitrogen balance, and body temperature were strongly indicative that chronic, low-level CO₂ (10 torr for 40 days) did not disturb the basic metabolic needs of the body.

Dose Response Trends in Chronic Exposures to Low-Level CO₂

Attempts were made to determine the dosage of CO₂ at which definable responses could be measured (Fig. 1 and 2 in this appendix section). One type of CO₂-dosage studied was the PICO₂ of the ambient environment in which the men resided for days at a time (Fig. 1). Using the "change" and "no change" data from the literature review, the alveolar and arterial PCO₂'s were found to change at PICO₂ 3.8 torr (Fig. 1a). The ventilatory responses appeared to be very sensitive to inspired CO₂ levels ≥ 6 torr. The venous plasma pH changes were variable, but the arterial pH's "changed" at PICO₂ ≥ 6 torr (Fig. 1b). The venous bicarbonate constant "changed" at PICO₂ > 6 torr. There was a "change" of the urinary ammonium

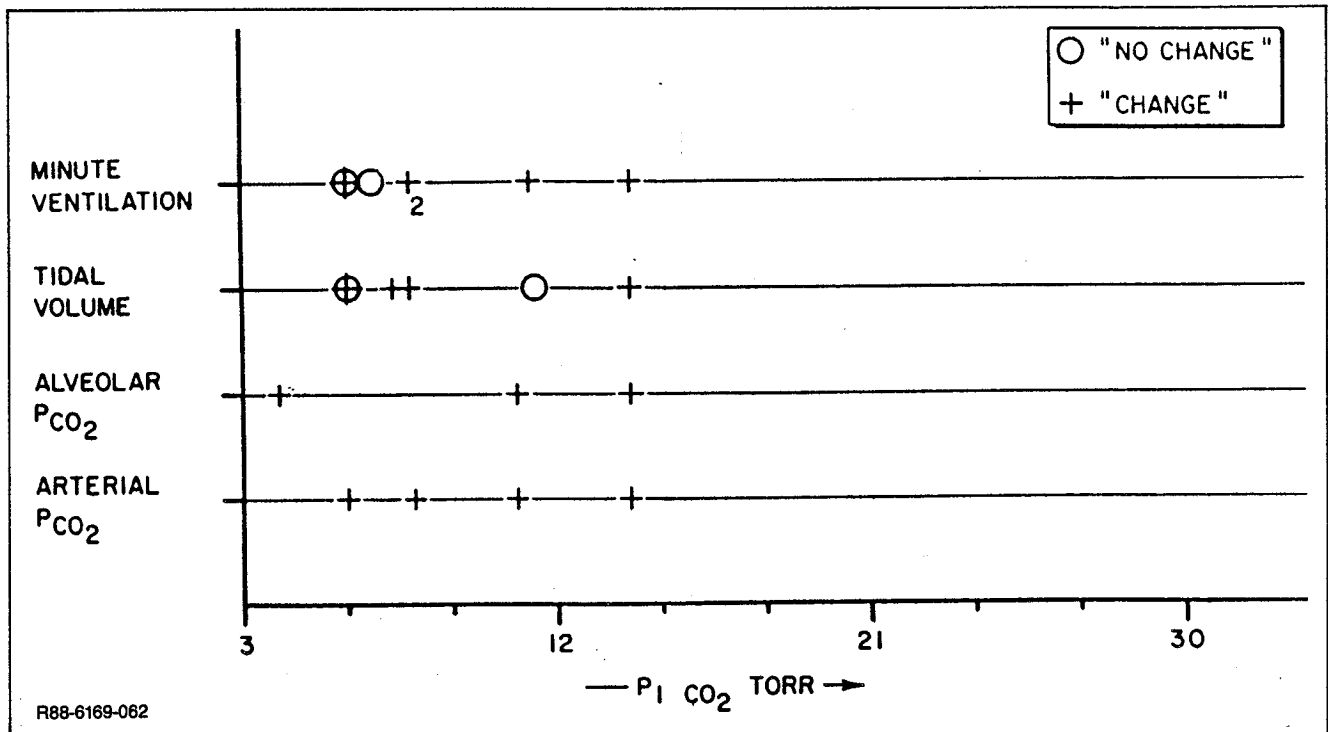


Fig. 1a

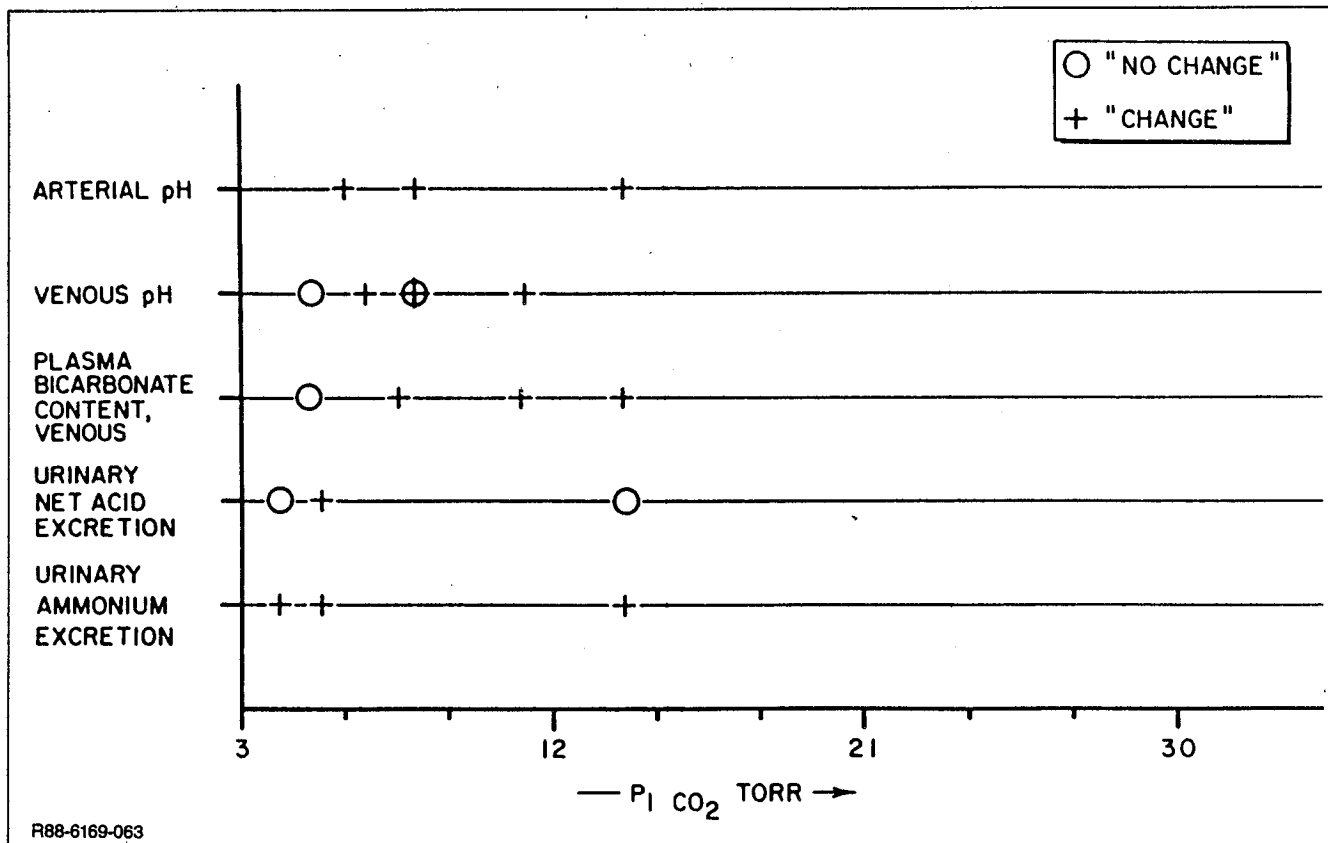


Fig. 1b

excretion above CO_2 levels of 3.8 torr but not necessarily a "change" of the urinary net acid excretion. The responses of the inorganic ions to low-level CO_2 were quite variable (Fig. 1c). The rates of urinary excretion of calcium and phosphorus "changed" over a wide domain of levels of CO_2 (5 to 30 torr). However, there were occasions when "no change" of the excretion of calcium and phosphorus occurred during exposures to $\text{PICO}_2 < 12$ torr. The plasma concentrations of calcium, sodium, and potassium showed both "changes" and "no changes" at CO_2 levels between 3 and 15 torr. In summary, acid-base balance and the blood gases were very sensitive to low levels of PICO_2 . The body fluid and electrolyte metabolism responded with great variability and showed no clear trend toward a threshold effect.

CO_2 doses were also examined by expressing them as a combined effect of CO_2 -level and duration-of-exposure. The product of PICO_2 and days-of-exposure (torr-days) was computed for those exposures whose responses were just discussed (Fig. 2). "Changes" occurred in the respiratory minute volume, PACO_2 , and arterial partial pressure of carbon dioxide (PaCO_2) when the CO_2 doses ≥ 150 torr-days (Fig. 2a). CO_2 doses ≥ 300 torr-days were accompanied by "changes" of the arterial pH, whereas the venous bicarbonate content and venous pH contained a mixture of "change" and "no change" with increased CO_2 dose (Fig. 2b). The urinary ammonium excretion "changed" and the urinary net-acid excretion did not necessarily change at CO_2 doses ≥ 150 torr-days (Fig. 2b). No dose-response trends were apparent for the response of the inorganic ions between 125 and 500 torr-days (Fig. 2c).

The nature of the dose-response trends from chronic, low level CO_2 exposures suggests that the ventilatory and acid-base functions "changed" above a threshold dosage. The respiratory minute volume transitioned from "no change" to "change" as the CO_2 doses rose above 7 torr and 300 torr-days (Fig. 1a,2a). The arterial and alveolar PCO_2 's always showed "change" down to 3.8 torr and 150 torr-days (Fig. 1a,2a); and there was no transition of PACO_2 or PaCO_2 into a "no change" status at low doses of CO_2 . There was no transition of the arterial pH into a "no change" status below the doses which showed "change," namely ≥ 6 torr and ≥ 300 torr-days (Fig. 1b and 2b). The notable feature of the responses of the inorganic ions to graded doses of CO_2 was the preponderant lack of a clear transition from "no change" to "change" (Fig. 1c,2c).

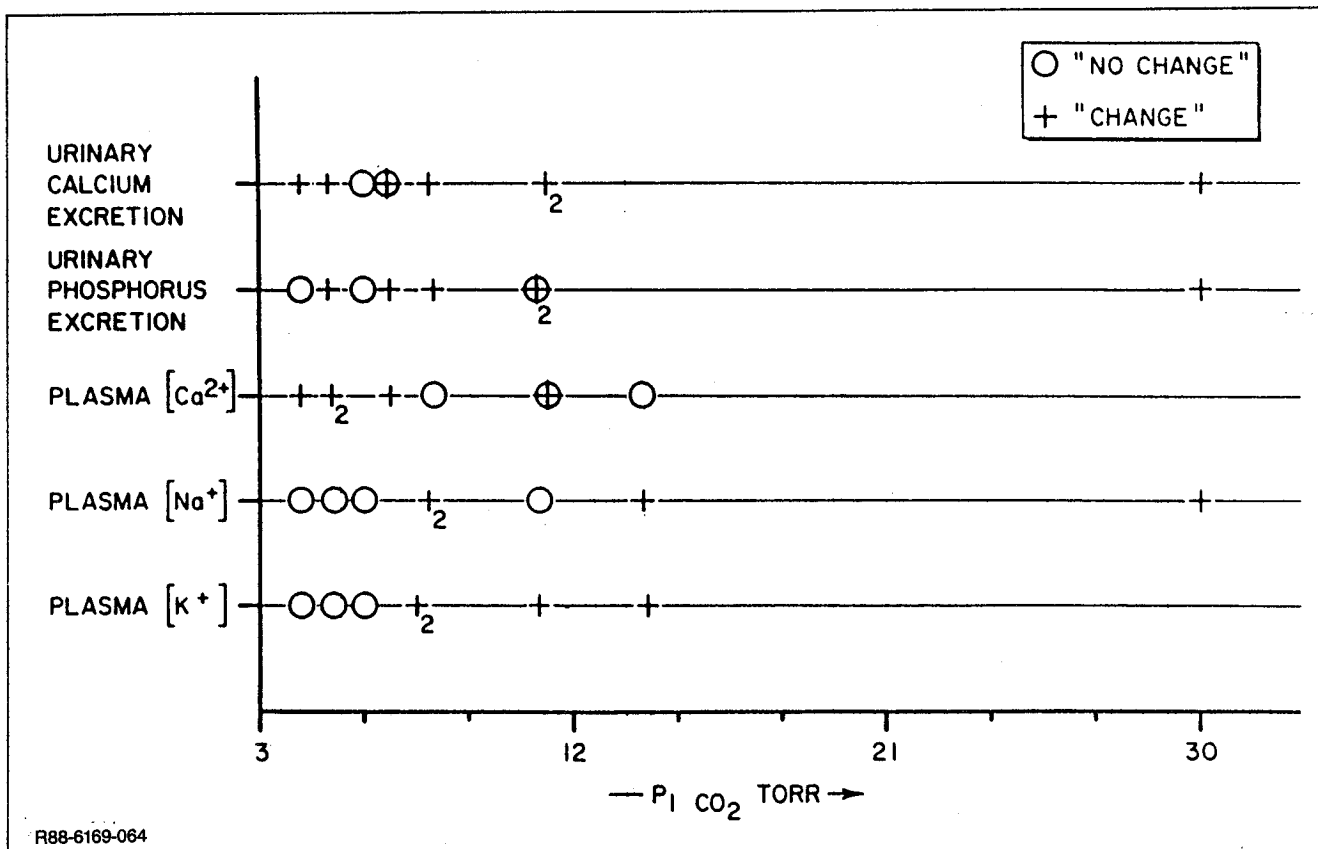


Fig. 1c

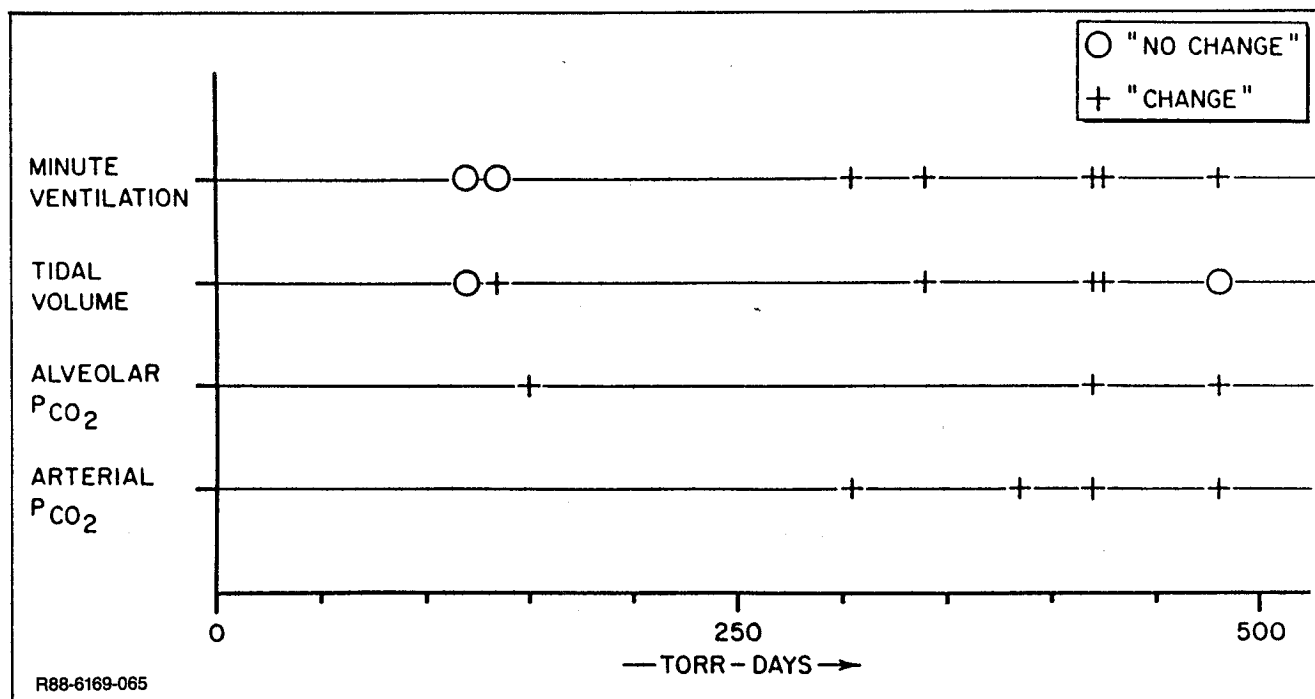


Fig. 2a

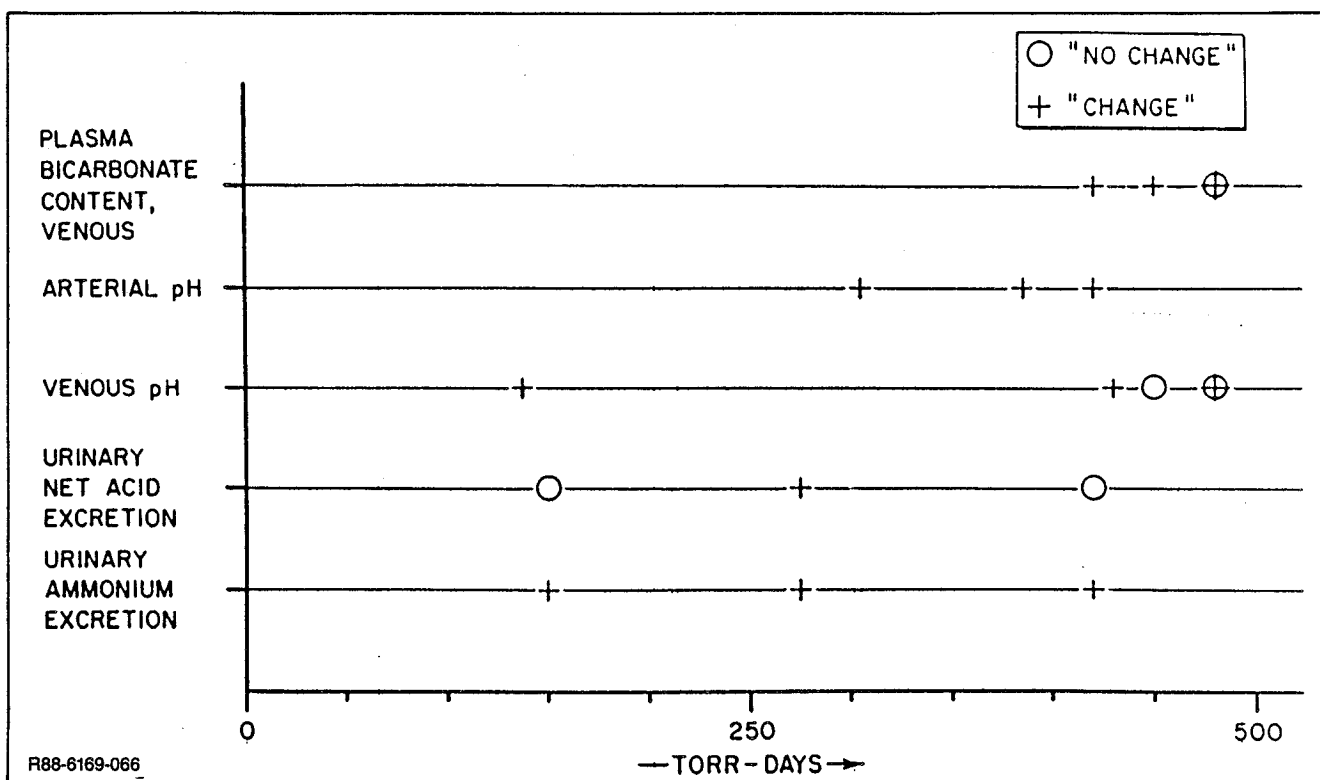


Fig. 2b

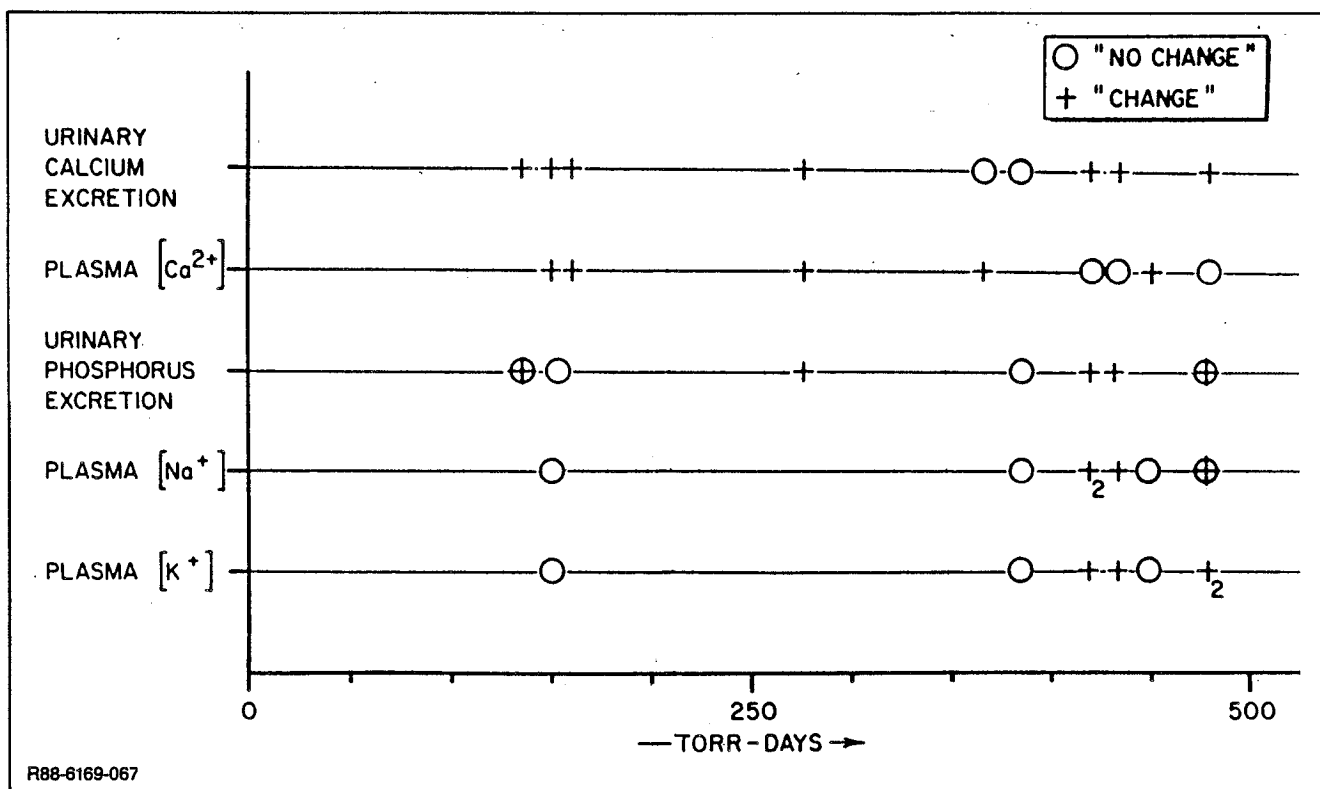


Fig. 2c

Thus, the threshold dosage of CO_2 below which many physiological functions do not "change" appears at $\text{PICO}_2 < 6$ torr; and at $\text{PICO}_2 \times \text{time} < 150$ torr-days (Fig. 1,2). Another way to view the primary and secondary responses to doses of chronic, low-level CO_2 is to perceive a continuum of functional responses as the doses become lower. At some point, the secondary responses may occur despite an absence of the primary responses. The reason for this is uncertain at this time.

Safe 90-Day Exposures

Laboratory Studies: 3.8-5 torr

The 90-day and 40-day human exposures to 3.8-5 torr resulted in no change of the pulmonary ventilation. The arterialized capillary pH fell by only 0.02 pH units, which is generally agreed to be a small, clinically insignificant change. The alveolar and mixed venous PCO_2 's rose by 1-1.5 torr, whereas the arterialized capillary PCO_2 rose 4 torr. The net-acid excretion by the urine was unchanged, but other urinary excretion rates of bicarbonate and ammonium ions rapidly rose to sustained levels during the CO_2 exposure. The subjects developed a positive sodium balance with a decline of their urinary excretion of Na^+ . Their plasma concentrations of Na^+ , water balance, magnesium balance, phosphorous balance, and potassium balance did not change. The body weights and 24-hour urinary volumes did not change. The calcium balance was transiently negative, the plasma levels and fecal excretion of calcium were increased, and the urinary excretion rate of hydroxyproline did not rise. The plasma vitamin D levels were decreased.

90-Day Exposures of Primates

At least two studies have been conducted in which the responses of primates were measured during continuous exposures to CO_2 for 90 days. Monkeys were exposed to 3% CO_2 and 21% for 93 days. The CO_2 -exposed monkeys fared as well as controls who were similarly confined in air. The CO_2 -exposed monkeys showed no significant changes of their body weight, activity, hematocrit, blood glucose, total leukocyte count, serum chloride, serum calcium, serum phosphorous, erythrocyte sedimentation rate, or serum bilirubin. Autopsied animals showed only the presence of mites in the lung. There was no evidence of adrenal impairment. Humans were exposed to 1% CO_2 at 0.7 ATA ($\text{PICO}_2 = 5$ torr) for 90 days. Analyses of frozen, anaerobic venous plasma samples suggested the existence of a mild respiratory acidosis during the middle and latter phases of the exposure to CO_2 . The data from

the CO₂-exposed subjects were statistically analyzed with respect to their values measured during the recovery from the exposure. Aside from a case of streptococcal infection, the subjects did not develop any significant medical problems during the CO₂ exposure. The combined information literally suggests that humans may be able to safely tolerate living in 5 torr CO₂ for 90 days without endangerment to their health. Noninjurious phases of respiratory acidosis may be expected to occur.

APPENDIX C

FAMILIARIZATION/ACTIVITY WITH UCD

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QUESTIONNAIRE

Familiarization During Training:

1. Have you ever donned/worn a UCD for familiarization?

_____ Yes _____ No

1.1 If No, why not?

(a) I felt it was not necessary.

(b) I was advised (by other crewmembers, crew systems technicians, etc) that the UCD was inadequate functionally or uncomfortable.

(c) It was not possible to achieve an adequate fit (to my satisfaction).

(d) It was too uncomfortable to don.

(e) Other; please explain: _____

1.2 If Yes, about how many times did you wear a UCD, and what was the duration of your longest period of wear?

(a) Only once or twice _____ hrs. _____ min.

(b) Less than 5 times _____ hrs. _____ min.

(c) More than 5 times _____ hrs. _____ min.

1.3 If you wore a UCD only once or twice, why?

(a) Familiarization was adequate, there was no need for further experience.

(b) It was uncomfortable; Explain nature of discomfort: _____

(c) Other; explain: _____

1.4 As part of familiarization, did you ever use or attempt to use the UCD?

_____ Yes _____ No

1.4.1 If not, why not?

(a) It was necessary for familiarization.

(b) I did not want to soil the equipment.

(c) I was concerned about leakage due to poor fit.

(d) I was concerned about leakage due to UCD reputation for failure.

(e) Other; explain: _____

1.4.2 If you used the UCD, was performance satisfactory?

_____ Yes _____ No If not, why?

(a) It leaked due to fit or failure. (Circle one).

- (b) It was physiologically difficult to use. (Urine flow was constricted by back pressure, folding of sheath, etc). Explain:

- (c) Other, explain: _____

2. Did you routinely wear a UCD during training exercises?

_____ Yes _____ No

2.1 If not, why not?

- (a) I felt it was not necessary. Typical duration of training sessions was less than _____ hr _____ min

- (b) It was too uncomfortable for routine wear; explain: _____

- (c) I felt it was unreliable (would leak if used).

- (d) No, but I wore the UCD for unusually long sessions (e.g., the Vacuum Chamber run in the Flight Hardware MMU with a suited period of about 7.5 hours).

- (e) Other; explain: _____

2.2 If you wore a UCD during one or more training sessions, did you use it?

_____ Yes _____ No

2.2.1 If not, why not?

- (a) There was no physiological need.
- (b) There was a physiological need, but I was concerned about leakage.
- (c) Other; explain: _____

2.2.2 If yes, was performance satisfactory?

_____ Yes _____ No If not, why not?

- (a) It leaked.
- (b) It was physiologically difficult to use (urine flow was constricted by back pressure, folding of sheath, etc.); explain: _____

- (c) Other; explain: _____

Actual EVA Experience with UCD:

3. For each EVA that you performed, please complete the following matrix:

EVA	Duration	UCD worn	UCD used
	___ hrs ___ min	Y/N	Y/N
1			
2			
3			
4			

For each EVA: (Repeat this section for each EVA)

3.1 If you did not wear the UCD, why not?

- (a) I did not feel it was needed.
- (b) I was too uncomfortable.
- (c) I did not have faith in its reliability and felt I could not use it safely in the zero-g environment.
- (d) Other; explain: _____

3.2 If you wore the UCD but did not use it, why not?

- (a) There was no physiological need.

(b) There was a physiological need, but I was concerned about leakage.

(c) Other; explain: _____

3.3 If you used the UCD, was performance satisfactory?

_____ Yes _____ No. If not, why not?

(a) It leaked.

(b) It was physiologically difficult to use (urine flow was constricted by back pressure, folding of sheath, etc). Explain: _____

(c) Other; explain: _____

Report Documentation Page

1. Report No. AS-EVALS-FR-8701		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Extravehicular Activities Limitations Study Volume 1 - Physiological Limitations to Extravehicular Activity in Space				5. Report Date August 1988	
				6. Performing Organization Code	
7. Author(s) Paul A. Furr, Ph.D. Conrad B. Monson, Ph.D. William J. Sears, Ph.D. Donald H. Peterson, M.E. Malcolm Smith, D.V.M. Robert L. Santoro, M.S.				8. Performing Organization Report No.	
				10. Work Unit No.	
9. Performing Organization Name and Address Grumman Corporation, Space Systems Division Bethpage, NY 11714				11. Contract or Grant No. NAS-9-17702	
				13. Type of Report and Period Covered Final	
12. Sponsoring Agency Name and Address NASA Lyndon B. Johnson Space Center Houston, TX 77058				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract This report contains the results of a comprehensive literature search on physiological aspects of EVA. Specifically the topics covered are: (1) Oxygen levels, (2) Optimum EVA work, (3) Food and water, (4) Carbon dioxide levels, (5) Repetitive decompressions, (6) Thermal, and (7) Urine collection. The literature was assessed on each of these topics, followed by statements on conclusions and recommended future research needs.					
17. Key Words (Suggested by Author(s)) Oxygen Repetitive decompression Carbon dioxide Decompression sickness Food Urine collection in space Water Thermal/temperature				18. Distribution Statement	
19. Security Classif. (of this report) Unclassified-Unlimited		20. Security Classif. (of this page) U		21. No. of pages 270	
				22. Price	